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A SURVEY OF OCEAN DIFFUSION STUDIES AND DATA

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A SURVEY OF OCEAN DIFFUSION STUDIES AND DATA

by

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TABLE OF CONTENTS

I. ABSTRACT

II. INTRODUCTION

III. TURBULENT DIFFUSION – A GENERAL REVIEW

IV. OCEAN DIFFUSION

- A. Okubo's Work
- B. Joseph and Sendner's Work
- C. Brooks's Work

V. EXPERIMENTAL RESULTS

VI. DISCUSSION

- A. Variation of Diffusivity with Scale
- B. Variation of Mean Square Dispersion with Time
- C. Variation of Dye Patch Area with Time
- D. Variation of Concentration with Time
- E. Variation of Concentration with Distance along Axis
- F. Variation of Concentration with Dye Patch Area

VII. CONCLUSIONS AND RECOMMENDATIONS

VIII. REFERENCES

IX. APPENDIX

X. FIGURES

I. ABSTRACT

A study was made of eddy diffusion in the ocean, with emphasis on the dispersion of sewage waste fields.

A thorough search of the literature on ocean diffusion was made, special emphasis being placed on publications of the 1959-1967 period. The object of the search was to review recent theoretical developments and to procure as much observational data as possible, for comparison with several theoretical models of ocean diffusion.

Equations for the dispersion of sewage fields, developed by N. H. Brooks, were compared with many observations of ocean diffusion and found to give good agreement with observed fact. The validity of other equations for ocean diffusion was also discussed.

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The help of Dr. Norman H. Brooks, who suggested this study and aided in the preparation of this technical memorandum is gratefully acknowledged.

II. INTRODUCTION

The generation and disposal of wastes by today's ever-increasing population has led to serious problems of pollution. The question of waste disposal into the environment concerns us all, for reasons of esthetics, health and economics.

The disposal of wastes into bodies of water is probably as old as man himself. In recent years, the coastal communities in the world have been disposing of their sewage in the ocean at ever-increasing rates. Many countries also deposit radioactive wastes at sea. The physical transport and dispersion of these wastes, i.e., their concentration in time and space after deposition, is an important consideration in any waste disposal problem.

Thus, the study of the turbulent diffusion of fluid in the ocean is of immense practical significance and deserving of serious consideration, as an important problem in the general field of turbulent diffusion, by engineers and scientists alike.

III. TURBULENT DIFFUSION — A GENERAL REVIEW

The theory of turbulent diffusion has developed steadily over the last fifty years. Diffusion in turbulent flow is due basically to mass transport by eddies which arise from the random velocity fluctuations of fluid particles. Much effort has been focused on defining and finding values for a coefficient of eddy diffusivity, from which can be derived the concentration and dispersion of "marked" fluid at various times and positions.

Several definitions, showing the wide range of thinking on this subject, are given below, after Orlob (1961).

Einstein introduced a diffusion coefficient for Brownian motion, defined as

$$D_z = \frac{1}{2} \frac{d(\sigma_z^2)}{dt} \tag{1}$$

where D_z is the diffusion coefficient in z-direction and has units of $(\text{length})^2/(\text{time})$, t = time, and σ_z^2 is the mean square dispersion, in the z-direction, of the diffusing particles.

In analogy to heat diffusion, Fick's Law relates the variation of concentration, c, of a substance to the eddy diffusivity by

$$\frac{\partial c}{\partial t} = D_z \frac{\partial^2 c}{\partial z^2} , \tag{2}$$

or, when D is a function of position,

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(D_z \frac{\partial c}{\partial z}\right) . \tag{3}$$

G. I. Taylor found that diffusion from a fixed point source due to continuous movements can be described when only the Langrangian time-correlation function, R_τ, and the mean square velocity, $\overline{w'^2}$, are known and wrote

$$D_z = \overline{w'^2} \int_0^\infty R_\xi \, d\xi \tag{4}$$

where

$$R_\xi = \frac{\overline{w'_t w'_{t+\xi}}}{\overline{w'^2_t}} \tag{5}$$

Prandtl saw an analogy between fluid turbulence and the "mean free path" idea of gas dynamics and defined eddy diffusion as

$$D_z = \ell_z \sqrt{\overline{w'^2}} \tag{6}$$

where ℓ_z is the mixing length and $\overline{w'^2}$ the mean square velocity fluctuation in the z-direction.

Richardson showed that the number of particles, n, which are situated in unit length at a distance, ℓ, from a particle is given by

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial \ell} \left[K(\ell) \frac{\partial n}{\partial \ell} \right] \tag{7}$$

in which K depends only on the separation of particles, ℓ. From recorded values of K and ℓ for atmospheric diffusion, Richardson found that almost all values fell on the line $K = 0.2\ell^{4/3}$. This relationship is known widely as the "four-thirds law".

Kolmogoroff, Batchelor and Obukhov, among others, later showed that for a subrange of eddies smaller than the scale of the turbulence the mean properties depend on the rate of energy dissipation, ϵ. By dimensional analysis, they derived the relationship

$$D \sim \epsilon^{\frac{1}{3}} L^{4/3}, \tag{8}$$

where L is the mean eddy size.

The idea that the concentration distribution of a particle, c(r, t), is the probability of the particle being at a given point at a given time has led to several statistical models for turbulent diffusion of particles in the ocean

based usually on the general statistical properties of isotropic and homogeneous turbulence. These are excellently reviewed in Okubo (1962).

Other approaches have also been used. Bowden (1965) described horizontal mixing in the sea due to a shearing current. Schönfeld (1962) introduced a concept of integral diffusivity, where the transport in turbulent flow is supposed to depend not so much on the local gradient of the concentration as on the distribution of concentration in a larger area. Gifford (1959) developed the statistical properties of a fluctuating plume dispersion model, where the total plume dispersion is separated into components of spreading and meandering. Harris (1963) used a statistical procedure, based on the method of maximum likelihood, for estimating the parameters of the one-dimensional diffusion process in a moving fluid.

Tchen (1959) studied the turbulent diffusion of particles on the basis of the statistical mechanics of the many-body problem and showed that the concentration of particles at the origin from a point source at the origin, $N_o(t, 0)$ was given by

$$N_o(t, 0) \sim t^{-s\gamma} ,$$

where t is the time, s is the number of dimensions, and γ is given according to $\gamma = 3/2$ for the inertial range of isotropic turbulence, $\gamma = 1$ for shear turbulence with a strong velocity gradient and $\gamma = 1/2$ for molecular diffusion with a constant diffusion coefficient. He also showed that the dispersion by diffusion ($\overline{r^2}$) was given by

$$\overline{r^2} \sim t^{2\gamma} . \qquad (9)$$

A good bibliographical coverage of recent contributions on turbulent diffusion in the oceans and atmosphere, especially for the years 1961-64, has been made by Brooks (1965).

IV. OCEAN DIFFUSION

A. Okubo's Work

Concerning the more specialized problem of diffusion in the ocean, Okubo (1962) has derived a general diffusion equation for the case of an instantaneous release of an amount M of a diffusing substance at $r_o = 0$ and $t_o = 0$. He uses the diffusion equation in the form, considering only radial diffusion,

$$\frac{\partial c}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left\{ af(t) \cdot r^{m+1} \frac{\partial s}{\partial r} \right\} \tag{10}$$

where r is the radial distance from the origin, a and m are arbitrary constants and f(t) is an arbitrary function of time related to the first two moments of the concentration distribution. Under the conditions that

(a) $c(r,0) = M\,\delta(r)/\pi r$

where $\delta(r)$ is the delta function

(b) $\lim_{r \to \infty} c(r,t) = 0$ for all $t \geq 0$

(c) $c(r,t) = 0$ for $r < 0$, all $t \geq 0$

(d) $\int_0^\infty c(r,t)\, 2\pi r dr = M$ for all $t \geq 0$,

the solution is given by

$$c(r,t) = \frac{(2-m)\,M}{2\pi(2-m)^{4/(2-m)}\,\Gamma\left(\frac{2}{2-m}\right) a^{2/(2-m)} \left\{\psi(t)\right\}^{2/(2-m)}} e^{-\frac{r^{(2-m)}}{(2-m)^2 a \psi(t)}} \tag{11}$$

where $\Gamma(\alpha)$ denotes the Gamma function ($0 \leq m < 2$) and $\psi(t) = \int_0^t f(t')dt'$.

For appropriate values of m and f(t), most of the previously derived equations for the concentration distribution can be systematically derived for radial diffusion:*

---

*from Okubo (1962) pp. 36-37.

(a) Fick's Law ($f(t) = 1$, $m = 0$)

$$c = \frac{M}{4\pi Kt} e^{-r^2/4Kt}$$

(K = diffusion constant)

(b) Joseph and Sendner (1958) ($f(t) = 1$, $m = 1$)

$$c = \frac{M}{2\pi P^2 t^2} e^{-r/Pt}$$ (P = diffusion velocity)

(c) Ozmidov ($f(t) = 1$, $m = 4/3$)

$$c(r, t) = \frac{M}{6\pi \gamma^3 t^3} e^{-r^{2/3}/\gamma t}$$ (γ = energy-dissipation parameter)

(d) Okubo and Pritchard, Pritchard (1959), ($f(t) = t$, $m = 0$)

$$c(r,t) = \frac{M}{\pi \omega^2 t^2} e^{-r^2/\omega^2 t^2}$$ (ω = diffusion velocity)

(e) Okubo (1962) ($f(t) = t$, $m = 2/3$)

$$c(r,t) = \frac{M}{(3/4)\pi^{3/2}\alpha^3 t^3} e^{-r^{4/3}/\alpha^2 t^2}$$ (α = energy-dissipation parameter)

(f) Obukhov ($f(t) = t^2$, $m = 0$)

$$c(r,t) = \frac{M}{\pi \beta^3 t^3} e^{-r^2/\beta^3 t^3}$$ (β = energy-dissipation parameter)

(g) The Schönfeld solution (1962) which cannot be derived from the above, is given by

$$c(r,t) = \frac{M}{2\pi} \frac{wt}{(w^2 t^2 + r^2)^{3/2}}$$ (w = diffusion velocity)

The behavior of the maximum concentration with time, $c(0,t)$ varies as t^{-1} for solution (a), t^{-2} for solutions (b), (d) and (g), and t^{-3} for solutions

(c), (e) and (f), whereas the mean square dispersion, σ^2, varies as t for solution (a), t^2 for solutions (b) and (d) and t^3 for solutions (c), (e) and (f).

B. Joseph and Sendner's Work

Joseph and Sendner's (1958) derivation was as follows: Assume that an amount M of a substance is introduced into the sea at t = 0 as a point source and is thereafter subject only to horizontal diffusion in a thin homogeneous and isotropic layer, so that all vertical variations may be neglected. Assume also that the turbulence field is stationary (i.e. properties invariant with time) and that it is possible to describe the distribution after time t by lines of equal concentration s. Assume that the lines of equal concentration are concentric circles for a statistically large enough series of observations and take the point of maximum concentration always as the origin.

Assume also that a diffusing particle in the mean moves away from the origin with a velocity independent of distance, where 2P is the mean velocity, and that the dispersion within a very small time interval increases linearly with increasing distance, at the rate 2Pr.

From these assumptions, they derived the following equation:

$$\frac{\partial s}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(Pr^2 \frac{\partial s}{\partial r} \right)$$

which, under the initial condition that the total amount M is concentrated in a point at t = 0, gives the following result:

$$s(r,t) = \frac{M}{2\pi (Pt)^2} e^{-r/Pt}$$

When a current U exists they added a convective term $U\frac{\partial s}{\partial r}$ to the right-hand side of the basic differential equation and, under the assumption that $U = \frac{U_o r_o}{r}$, they wrote

$$\frac{\partial s}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(Pr^2\frac{\partial s}{\partial r}\right) - \frac{U_o r_o}{r}\frac{\partial s}{\partial r} \ .$$

For a steady state problem, where $\frac{\partial s}{\partial t} = 0$, and when $s = s_o$ at $r = r_o$ and $s = s_1$ at $r = r_1$, this results in

$$\frac{s-s_1}{s_o-s_1} = \frac{\Delta s}{\Delta s_o} = \frac{1 - \exp\left[-\frac{U_o}{P}\left(\frac{r_o}{r} - \frac{r_o}{r_1}\right)\right]}{1 - \exp\left[-\frac{U_o}{P}\left(1 - \frac{r_o}{r_1}\right)\right]}$$

which reduces, when $r_1 = \infty$ and $s_1 = 0$, to

$$\frac{s}{s_o} = \frac{1 - \exp\left[-\frac{U_o r_o}{P r}\right]}{1 - \exp\left[-\frac{U_o}{P}\right]}$$

or,

$$\frac{s}{s_o} = (\text{constant}).\left(1 - e^{-\frac{U_o r_o}{P}\cdot\frac{1}{r}}\right) \ .$$

Joseph and Sendner later extended their theory (1962) to the case where P varies slowly as r and wrote

$$P(r) = P_o(r/r_o)^{\lambda-1}$$

where $\lambda = 1$ corresponds to the case P = constant. They found, for observations on the spread of radioactive material attributed to T. R. Folsom and A. C. Vine, that $\lambda = 0.83$ where $P_o = 1.6$ cm/sec and $r_o = 12.5$ km. For the mixing of Mediterranean water in the Atlantic Ocean, observations of salinity led to the value $\lambda = 0.70$, with $P_o \sim 1$ cm/sec and $r_o = 100$ km.

The formula for the concentration, for P varying with r as above, can be found by substituting the values $m = \lambda, f(t) = 1$ and $a = P_o r_o^{(1-\lambda)}$ into Okubo's general formula.

Noble (1961) and Olson (1964) applied the Joseph and Sendner formula to the case where the dye patch is initially of radius R_o with uniform concentration c_o^* and showed that the resulting concentration at the center of the patch could be described by

$$c = c_o^* \left[1 - e^{-R_o/Pt} \left(1 + \frac{R_o}{Pt}\right) \right]$$

C. Brooks's Work

The basic Fickian equation was used by Brooks (1960) to describe the dispersion of sewage effluent from a line source in an ocean current, such as a typical sewage diffuser at the end of a submarine outfall pipe.

He assumed that the diffusion law with variable eddy diffusivity K was valid, i.e.,

$$\text{Flux in x-direction} = -K \frac{\partial c}{\partial x}.$$

Other assumptions were that K is a function of the scale L, (taken as the width of the sewage field); vertical mixing is negligible; longitudinal mixing is negligible; and the flow is steady. He also considered the disappearance rate of coliform organisms, present in sewage effluent, due to mortality and sedimentation, to be proportional to concentration (-kc). Since this effect is only to multiply the concentration by the factor $e^{-k\frac{x}{U}}$, where U is the current velocity and x is the distance from the source along the current, this effect will be left out of further consideration, so that only the physical dilution of the sewage is considered.

The convective diffusion equation is thus

$$\frac{\partial}{\partial y}\left(-K\frac{\partial c}{\partial y}\right) + U \frac{\partial c}{\partial x} = 0 \qquad (12)$$

The problem under consideration is shown schematically in Fig. 1, where the substance being diffused is discharged along a line of length b at a uniform concentration, C_o.

Since K is a function of the distance x along the plume (and not the distance y across the plume):

$$K \frac{\partial^2 c}{\partial y^2} = U \frac{\partial c}{\partial x} , \tag{13}$$

Introducing $K = K_o f(x)$ where $K = K_o$ at $x = 0$ and a new variable x' such that $dx' = f(x)dx$, Brooks arrived at the classical heat diffusion equation

$$\frac{\partial^2 c}{\partial y^2} = \frac{U}{K_o} \frac{\partial c}{\partial x'} , \tag{14}$$

for which the solution is, under the given initial conditions (see Crank (1956) and Carslaw and Jaeger (1959)),

$$c(x, y) = \frac{C_o}{2\pi K_o t'} \int_{-b/2}^{b/2} \exp \frac{-(y-y')^2}{4K_o t'} \, dy' = c(x', y) , \tag{15}$$

where $t' = x'/U$ for convenience. He also defined L, the field width, as $2\sqrt{3}\sigma$ * where σ is the standard deviation given by

$$\sigma^2 = \frac{1}{C_o b} \int_{-\infty}^{\infty} y^2 \, c(x, y) \, dy . \tag{16}$$

For the three cases of: (1) K = constant; (2) K increasing linearly with L; and (3) K proportional to $L^{4/3}$, the relationships of x' to x and L to x are given by Table 1, in which b = initial width of sewage field (i.e. L = b at x = 0), and β is a dimensionless parameter $\beta = \frac{12K_o}{Ub}$.

Table 1

Case I:	$K = K_o$	$\frac{L}{b} = (1 + 2\beta\frac{x}{b})^{1/2}$	$x' = x$
Case II:	$\frac{K}{K_o} = \frac{L}{b}$	$\frac{L}{b} = 1 + \beta\frac{x}{b}$	$x' = \frac{b}{2\beta}\left[(1+\beta\frac{x}{b})^2 - 1\right]$
Case III:	$\frac{K}{K_o} = (\frac{L}{b})^{4/3}$	$\frac{L}{b} = (1+\frac{2}{3}\beta\frac{x}{b})^{3/2}$	$x' = \frac{b}{2\beta}\left[(1+\frac{2}{3}\beta\frac{x}{b})^3 - 1\right]$

* so that L = b at x = 0. Normally L is defined as 4σ.

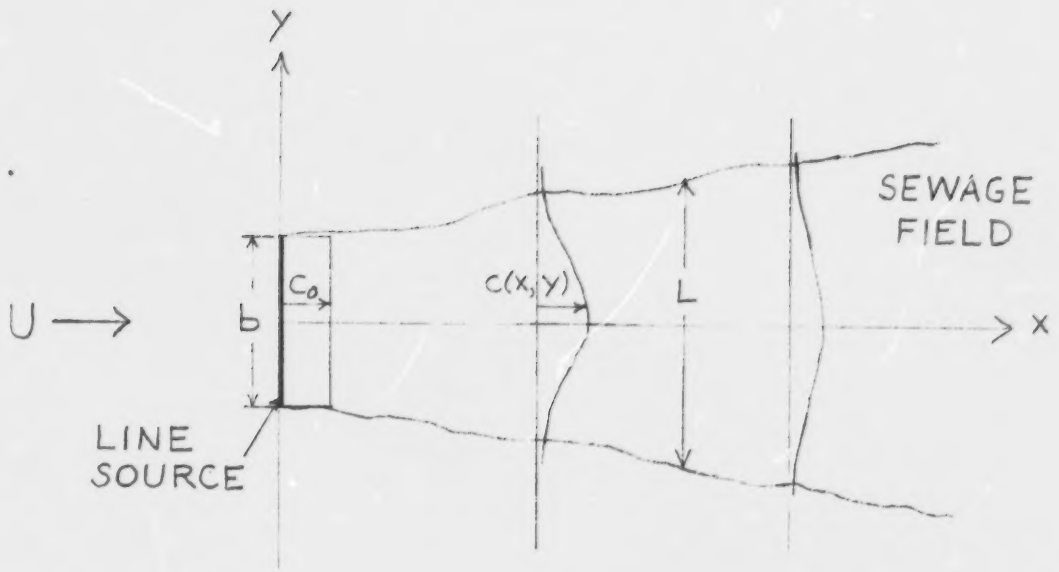

FIG. 1 (AFTER BROOKS (1960))

RADIAL SPREADING OF A PLUME

FIG. 2

For the maximum concentration, which occurs along the center line of the field, y = 0, the results are given in Table 2,

Table 2

Case I:	$K = K_o$	$C_{max}(x) = C_o \, \mathrm{erf}\left\{\sqrt{\frac{3}{4\beta x/b}}\right\}$
Case II:	$\frac{K}{K_o} = \frac{L}{b}$	$C_{max}(x) = C_o \, \mathrm{erf}\left\{\sqrt{\frac{3/2}{(1+\beta\frac{x}{b})^2-1}}\right\}$
Case III:	$\frac{K}{K_o} = (\frac{L}{b})^{4/3}$	$C_{max}(x) = C_o \, \mathrm{erf}\left\{\sqrt{\frac{3/2}{(1+\frac{2}{3}\beta\frac{x}{b})^3-1}}\right\}$

where erf denotes the standard error function

$$\mathrm{erf}(X) = \frac{2}{\sqrt{\pi}} \int_o^X e^{-v^2} \, dv \, . \qquad (17)$$

Brooks extended his solutions for the different assumptions (1964)(1966) to the case of steady flow from a point source by letting $b \to 0$ in the equations and writing $C_o b = M$. For the maximum concentration along the center line of the plume the results are shown in Table 3.

Table 3

Case I:	$K = K_o$	$C_{max}(x) = \frac{M}{2\sqrt{\pi K_o}} (\frac{x}{U})^{-1/2}$
Case II:	$K = \alpha' L$	$C_{max}(x) = \frac{M}{2\sqrt{6\pi\,\alpha'}} (\frac{x}{U})^{-1}$
Case III:	$K = \alpha L^{4/3}$	$C_{max}(x) = \sqrt{\frac{3}{256\pi}} \frac{M}{\alpha^{3/2}} (\frac{x}{U})^{-3/2}$

For a more general approach to diffusion from a point source in a current, it is preferable to start with the basic equation

$$K \frac{\partial^2 c}{\partial y^2} = \frac{\partial c}{\partial t} \, , \qquad (18)$$

Brooks (1966) used the following analysis:

Let: $\sigma = \sigma(t)$ only (19a)

$K = \alpha(m\sigma)^n$, α, m, and n are constants ($n < 2$) (19b)

Define : $Kdt = dt'$ (19c)

$t = \frac{x}{U}$, M = strength per foot of depth of continuous point source at origin (19d)

then $\frac{\partial^2 c}{\partial y^2} = \frac{\partial c}{\partial t'}$, (19e)

and the solution is then given by

$$c(y, t') = \frac{M}{2(\pi t')^{\frac{1}{2}}} e^{-y^2/4t'} \tag{20}$$

From equation (20), it may be shown that $\sigma^2 = 2t'$, and using equations (19b) and (19c) and integrating:

$$t' = \left[(1 - \frac{n}{2})\, \alpha m^n 2^{n/2} t\right]^{2/2-n} \tag{21}$$

Table 4 shows t' values for several selected n, along with corresponding σ and C_o values, where C_o is the value of c at the center of the spreading plume.

Table 4

Results for one-deminsional point source for various diffusion laws

1. $n = 0$	$t' = \alpha t$	$\sigma = \sqrt{2\alpha t}$	$C_o = \frac{M}{2\sqrt{\pi \alpha t}}$
2. $n = 1$	$t' = \frac{1}{2}\alpha^2 m^2 t^2$	$\sigma = \alpha m t$	$C_o = \frac{M}{\sqrt{2\pi}} \cdot \frac{1}{\alpha m t}$
3. $n = \frac{4}{3}$	$t' = \frac{4}{27}\alpha^3 m^4 t^3$	$\sigma = \sqrt{\frac{8}{27}}(\alpha t)^{3/2} m^2$	$C_o = \frac{3\sqrt{3}}{4\sqrt{\pi}} \frac{M}{m^2 \alpha^{3/2} t^{3/2}}$

These results may be generalized to two and three dimensions, following Brooks (1966) and Tchen (1959), to write:

Table 5

$C_o \sim t^p$ $\sigma \sim t^q$						
	1 dimension		2 dimensions		3 dimensions	
Exponents	p	q	p	q	p	q
1. K = constant	-1/2	1/2	-1	1/2	-3/2	1/2
2. $K \sim L$	-1	1	-2	1	-3	1
3. $K \sim L^{4/3}$	-3/2	3/2	-3	3/2	-9/2	3/2
4. $K \sim L^n$	$-\frac{1}{2-n}$	$\frac{1}{2-n}$	$-\frac{2}{2-n}$	$\frac{1}{2-n}$	$-\frac{3}{2-n}$	$\frac{1}{2-n}$

The 2-dimensional case may be considered as a patch spreading in two dimensions from an instantaneous source or a plume from a continuous source spreading radially in a plane perpendicular to the current (Fig. 2). The three-dimensional case is for an instantaneous point source only.

It should be noted that the Brooks solution in two dimensions,

$$c(r,t) = \frac{M}{4\pi t'} e^{-r^2/4t'}, \qquad (22)$$

is equivalent to that of Obukhov on page IV-2 with β, the energy-dissipation parameter, equal to $\frac{2^{4/3}}{3} \alpha m^{4/3}$.

The theories developed in this section will be applied to the experimental data collected in the literature search to test their validity. The factor of dimensions will also be considered. It is desired to find out which formula may most appropriately be used to predict the dispersion of sewage effluent in the ocean.

V. EXPERIMENTAL RESULTS

Since the most important dispersion mechanism in streams and estuaries is usually longitudinal dispersion and since this paper is limited to lateral dispersion, no mention of dispersion in streams and estuaries will be made, with one exception.

A cursory glance at the literature revealed many studies of dispersion in estuaries, and the reader is referred to the work of Bowden (1962)(1967), Eggink (1966), Gordon (1959), Harleman and Ippen (1961), Hetling and O'Connell (1966), Higuchi (1967), Holley and Harleman (1965), O'Connor, et al. (1963), Pritchard and Carpenter (1960) and Pyatt (1964). This is but a short list of the more recent contributors in this field and is not intended to be complete.

Horizontal diffusion in the Great Lakes was studied by Csanady (1963) and Noble (1961). Parker (1961) examined eddy diffusion in a reservoir, while Alsaffar (1966) described lateral diffusion in a tidal estuary. Diachishin (1963) described dye dispersion in the Delaware Estuary model and gave data from studies in the Irish Sea by Wright. Surface dispersion in the laboratory was considered by Gray and Pochapsky (1964), Masch (1962) and Orlob (1961).

Many men have measured horizontal eddy diffusion in the ocean during the last thirty years. Excellent summaries of the work done up to 1955, 1961 and 1964 are given in Pearson (1956), Okubo (1962) and Wiegel (1964), respectively. Where possible, the original sources were consulted for data, in order to ascertain more clearly the nature of the measurements and to eliminate any errors which might have arisen through transferring data from one report to another.

The turbulent diffusion in the ocean of dyes, floats, radioactivity and other tracers had been reported by many up to 1959. Although credit cannot be given to all, major efforts were made by Stommel (1949); Seligman (1955); Joseph and Sendner (1958); Japanese Governmental Agencies (1958); Bowles (1967); Gunnerson (1959); and Folsom and Vine, Munk, et al., Okubo, et al., Sverdup, Hidaka, Proudman, Richardson and Stommel, as described in Okubo (1962).

Since 1959 a great number of observations have been made on various aspects of horizontal diffusion in the ocean, reflecting the increased interest in this problem, as well as the development of improved tracers and methods of detection. Important contributions have been made by Bourret and Broida, (1960); Hancock Foundation (1965); Carter and Okubo (1965); Carter, et al. (1967); Costin (1965); Wright, reported in Diachishin (1963); Foxworthy, et al., (1966); Fyn (1965); Fukuda, et al. (1964); Gunnerson (1961); Harris, et al., (1962); Hume and Garber (1966); Ichiye (1962) (1965); Ichiye and Olson (1960); Ichiye, et al., (1964); Joseph and Sendner (1962); Joseph, et al. (1964); Larsen (1965); Miyake and Saruhashi (1959); Oakley and Dyer (1966); Okubo (1962) (1965); Olson and Ichiye (1959); Pritchard and Carpenter (1965); Reinert (1965); Thomas (1962); and Waldichuk (1966).

A listing of experimental data is given in Table 6. Most of the experimental data is given in the Appendix in Tables A-1, A-3, A-5, A-7 to A-9. The symbols used in Figures 3-5 are given in the Appendix in Tables A-2, A-4 and A-6 and on the graphs for Figure 3-45. The data were gathered from tables and the text, whenever possible, and from published graphs in the various reports.

TABLE 6
EXPERIMENTAL DATA

Reference No.	Investigator and/or Source of Data	Experiments or Observations	Sea Area	Dimensions
1	A. M. Alsaffar	Floating Particles (Wooden Disks)	San Joaquin River Tidal Estuary	2
2	Bourret & Broida	Floats (Sheets of Mimeo Paper)	Atlantic Ocean, East of Elliott Key	2
8	Bowles	Radioisotopes	Off Dorset Coast, Eng.	3
17	Carter & Okubo	Dye Patch	Cape Kennedy area	2 & 3 (releases 3-6)
18	Carter, et al.	Dye Patch	Seaside Heights, N. J.	2
19	Costin	Dye Patch	Bahama Banks	3(?)
21	Csanady	Drogues, Bottles & Paper	Lake Huron	
22	Diachishin	Dye Patch	Delaware Model	2
	Wright	Radioisotopes (?)	Irish Sea	2(?)
27	Fukuda, et al.	Dye Patch & Chlorinity	E. Coast of Japan	2
30	Gray and Pochapsky	Disks of Paper	Indoor Tank	2
31	Gunnerson	Dye Stream	Santa Monica Bay	2
32	Gunnerson	Dye Stream	Santa Monica Bay	2
33 25	Hancock Foundation (Foxworthy, et al.)	Dye Patch	off Southern California	2 & 3 (down to 6')
37	Harris, et al.	Dye Stream	S. Coast of Natal	2-3 (?)
42	Hyperion Engrs.	Sewage Field	Various Coastal Outfalls in U.S.	2
44, 46	Ichiye	Dye Patch	Off New Jersey S. of Long Island on Bahama Banks	2
45 (Also Ref. 3, Ref. 6)	Ichiye & Olson	Olson - Drift Card Ichiye - Drift Bottle Stommel - (Paper, Dye Spots) Platania - Drift Bottle		2
47	Japanese Govt. Agencies	Dye Patch	Off Tokai-Mura	2
48	Joseph & Sendner	Turbidity	North Sea	2
	Folsom & Vine	Radioisotopes	Open Sea	2
	J. Joseph	Extinction (Turbidity)	Irminger Sea	2
	Wüst	Diff. of Med. Sea into Atlantic Ocean	Atlantic Ocean	2 & 3(?)
50	Joseph, et al.	Dye Patch	North Sea	2
53	Masch	Floating Particles	Laboratory channel	2
54	Miyake & Saruhashi	Radioisotopes	North Pacific	3(?)
57	Noble	Dye Patch	Lake Michigan	2
58	Oakley & Dyer	Salinity	Mouth of Tyne R., U. K.	2-3(?)
61	Okubo (CBI)	Dye Patch	York River Estuary	1
	" "	Dye Patch	Off Cape Canaveral	2
	Okubo, et al.	Dye Patch	Off Tokai-Mura	2
	Sverdup	Dye	Open Sea	2
	Seligman	Dye	Irish Sea	2
	Folsom & Vine	Radioactivity	Open Sea	2
	Joseph & Sendner	Turbidity	North Sea	2
66	Orlob	Floating Particles	Laboratory Channel	2
67	Parker	Radioisotopes (?)	Reservoir	2
	Burke (1946)	"	"	"
68	Pearson			
	Sverdup	Dyes	Pacific Ocean	2
	Munk, et al.	Radioisotopes	Bikini Lagoon	1
	von Arx	Dyes	Bikini Lagoon	2
	Ketchum	Iron Waste	New York Bight	2
	Richardson & Stommel	Parsnips	Loch Long, Scotland	2
	Stommel	Dye Patches, Mimeo Papers	Atlantic Ocean	2
	Hanzawa	"	"	2(?)
	Hidaka	"	"	2(?)
	Proudman	"	"	2(?)
71	Pritchard & Carpenter	Dye Patch	Baltimore Harbor Chesapeake Bay	
74	Reinert	Dye Patch	Long Island Sound	2(?)
76	Seligman	Dye Patch	Irish Sea	2
77	Stommel	Floating Particles	Atlantic Ocean	2
80	Thomas	Radioisotopes	New Zealand Coast	2(?)
81	Waldichuk	Dye Patch	off Vancouver Island	2
82	Wiegel	Moon & Harleman Data	"	2(?)

VI. DISCUSSION

A. Variation of Diffusivity with Scale.

As indicated in Section III-A, the lateral coefficient of eddy diffusivity, K_y, may be defined as

$$K_y = \frac{1}{2} \frac{d(\sigma_y^2)}{dt} , \tag{24}$$

or, for the steady-state case, with constant current of speed U, as

$$K_y = \frac{U}{2} \frac{d(\sigma_y^2)}{dx} , \tag{25}$$

where x is the distance along the current.

Thus the diffusion coefficient may be determined from measurements of the rate of change of σ_y^2, usually as

$$K_y = \frac{\sigma_2^2 - \sigma_1^2}{2(t_2 - t_1)} \tag{26}$$

For experiments of the scatter of particles in the ocean, the Richardson law may be used to determine the neighbor diffusivity, which is defined as

$$F(\ell) = \frac{\overline{(\ell - \ell_o)^2}}{2t} \tag{27}$$

where ℓ_o is the initial separation of two particles, ℓ a later separation, t the time taken to separate by the distance $(\ell - \ell_o)$ and the $\overline{\quad}$ denotes the spatial average. The length scale in this case may be defined as ℓ_o, if ℓ is not much different from ℓ_o, or as $\frac{(\ell + \ell_o)}{2}$, if ℓ and ℓ_o differ a lot.

The coefficient of eddy diffusivity has also been determined by fitting observed results for the changes of concentration with time and position to theoretical models for dye diffusion. It is felt, however, that the use of equation 26 offers the best chance for avoiding confusion in determinations of K_y. The values of σ are determined with respect to the centroid of the plume, usually without allowing for timewise fluctuation of the plume.

For the scale of the phenomenon, the use of the expression $L = 4\sigma$ is recommended since this width (-2σ to $+2\sigma$) contains 95% of the diffusant for a normal distribution of lateral concentration. (For the Brooks solution for a line source, $L = 2\sqrt{3}\sigma$ should be used so that $L = b$ when $x = 0$.)

Thus for a dispersing sewage field from a point source, the expression

$$K_y = \frac{1}{32} \frac{w_2^2 - w_1^2}{(t_2 - t_1)} \tag{28}$$

may be used to determine K_y, where w_1 and w_2 are the observed sewage field widths at t_1 and t_2, respectively.

As for the relationship between the neighbor diffusivity $F(\ell)$ and the eddy diffusivity K_y, Stommel (1949) states that $F(\ell) \cong 3.03K$ when the "four-thirds law" holds, and $F(\ell) = 2K$ when $F(\ell)$ is independent of ℓ.

Figure 3 shows the increase in K_y with increasing scale L.* The K_y values shown range from 10^{-1} cm^2/sec to 10^9 cm^2/sec for changes in scale from 10^0 cm to 10^9 cm. Thus the assumption of a constant diffusion coefficient is obviously invalid for ocean diffusion.

It should be noted that one would intuitively expect the diffusivity to increase with the scale of the phenomenon, since a diffusing patch is dispersed only by eddies of characteristic size smaller than the patch. Hence, many larger eddies, which may only cause meandering and not dispersion of the diffusant when it is concentrated at first in a small area, are gradually brought into play, and cause dispersion within a diffusing patch, instead of only advection of the whole patch, as the patch area grows larger. Thus it is assumed that the diffusivity increases as some power of the scale, say $K = \alpha L^n$. Many least-squares fittings have shown that the "four-thirds law" is a good description of this increase with scale, and its theoretical derivation, based on the similarity of the diffusion of mass and momentum (see Stommel, (1949)), leads one to believe that this law may be a good description of the oceanic dispersion mechanism. On the figure, several lines representing the "four-thirds law" are shown, for various values of the constant α in the expression $K = \alpha L^{4/3}$.

*In Figure 3, the values for $F(\ell)$ are not adjusted for the relationship $F(\ell) \cong 3.03K$, but on log-log graph paper this difference is not too significant, considering the general data scatter. (Figure 3 and all subsequent ones are placed after the Appendix of data tables.)

It is seen that the agreement of the "four-thirds law" with observed data is especially good in the middle range of L, from about 10 meters to 10 kilometers. This range is the one of practical significance in ocean outfall calculations. The values shown for α are 0.02, 0.01 and 0.005cm$^{2/3}$/sec. among those most commonly reported.

In the lower ranges of L and K are many values which seem to fit a line $K = 0.05L^{4/3}$ reasonably well. Most of these values are from laboratory investigations by Orlob (1961), in which he used a varying value for the energy dissipation E and showed that $K = \alpha' E^{1/3} L^{4/3}$ as is theoretically predicted for a varying E. In the ocean E is usually assumed constant although the validity of this assumption is certainly questionable; however, it enters as only the 1/3 power. Also included are reported results of Harleman (Orlob, 1961), Sverdup (Pearson, 1956) and Burke (Parker, 1961) which the author was not able to examine directly and hence which may not be applicable to the problem at hand. Also, the results of Alsaffar (1966) for lateral diffusion in a tidal estuary are not really applicable to the ocean problem.

When Okubo's (Okubo, 1962) determination of Obukhov's energy-dissipation parameter, β, is matched to the Brooks equation (where $\alpha = \frac{3}{16}\beta$ for $L = 4\sigma$ and α given by $K = \alpha L^{4/3}$), the result is $K = 6.9 \times 10^{-3} L^{4/3}$.

The scatter of values of K for L greater than 100 km (10^7cm) may be explained partially by the difficulty of making precise measurements of the extent, lateral and vertical, of a diffusant spread over such large areas. It may also be that there is large anisotropy and little homogeneity in the ocean over such large distances. Also, the turbulent eddies may be expected to reach limiting values in this range of L and thus one would expect the diffusion coefficient to gradually approach a constant value.

Thus, the results of over forty independent studies of turbulent dispersion seem to reasonably support the "four-thirds law" in the ranges applicable to oceanic turbulence (10 meters - 100 kilometers), and the assumption that the diffusivity increases only linearly with the scale, made in the theories of Joseph and Sendner (1958) and Okubo and Pritchard (Pritchard, 1959), is seen to be a less satisfactory fit of ocean diffusion data over a wide range.

In the absence of a least-squares fitting*, the value of α in $K = \alpha L^{4/3}$ will be taken 0.02, 0.01 and 0.005 $cm^{2/3}/sec$ in applying Brooks's equations to observations of ocean diffusion.

B. Variation of Mean Square Dispersion with Time

The variation of the mean square dispersion in the lateral direction, σ_y^2, of the diffusing particles is of interest because it determines the width of the diffusing patch with distance or time from the source and because it provides an independent check on the validity of theoretical assumptions for the concentration distribution and the validity of the "four-thirds law".

The lateral mean square dispersion is usually defined as

$$\sigma_y^2(t) = \frac{\int_{-\infty}^{\infty} y^2 c(y, t)\, dy}{\int_{-\infty}^{\infty} c(y, t)\, dy} \tag{29}$$

or, for the two-dimensional case, as

$$\sigma_r^2(t) = \frac{\int_{o}^{\infty} r^2 c(r, t)\, 2\pi r\, dr}{\int_{o}^{\infty} c(r, t)\, 2\pi r\, dr} \tag{30}$$

For simple Fickian diffusion, the concentration, c, of diffusant, for an instantaneous point-source release of an amount M may be written in two dimensions (with axial symmetry) as:

$$c = \frac{M}{4\pi\sigma_r}\, e^{-r^2/2\sigma_r^2} \tag{31}$$

provided the diffusion coefficient is constant or depends only on time or scale (σ_r).

*For a detailed comparison of theoretical predictions and experimental data concerning the variance of K with L, including several least-squares fittings to data, the reader is referred to Okubo (1962), especially pages 70, 90, 92 and 117.

where σ_r^2 is the horizontal mean dispersion. Hence the concentration for r = 0, i.e., at the center of the diffusing patch, depends on the time-dependence of σ_r^2. Also the diffusivity is related to σ_y^2 by $K_y = \frac{1}{2}\frac{d(\sigma_y^2)}{dt}$, or to σ_r^2 by $K_r = \frac{1}{2}\frac{d(\sigma_r^2)}{dt}$.

If we assume that $\sigma_y^2 = \alpha t^n$ or $\sigma_y^2 = \beta x^p$, then the "four-thirds law" predicts n and p equal to three. For the various concentration distributions proposed (Okubo, 1962), σ^2 varies as t for a constant diffusivity (Fickian solution), t^2 for diffusivity directly proportional to scale (Joseph and Sendner, Okubo and Pritchard) and t^3 for diffusivity following the "four-thirds law" (Ozmidov, Okubo, Obukhov, Brooks). Figure 4 shows the values of σ^2 found plotted against time. The t^3 law seems to give a better fit to the data than the t^2 law, although the considerable data scatter inhibits a conclusive judgment. For experimental data up to 1962, Okubo (1962, p. 88) found a least-squares fitting $\sigma^2 \sim t^{2.54}$. In experiments off Southern California, the Hancock Foundation (1965) found σ_y^2 varying with powers of t ranging from .63-1.8 in the case of an instantaneous release, and with powers of x ranging from 1.30-2.24 in the case of a continuous source.

In all cases a least-squares fitting was used. For two experiments where the actual values were given, it is seen from Figure 4 that these data are reasonably approximated by the line $\sigma^2 = .025t^3$ (cgs units) (i.e., $\alpha = 0.02$). It may also be seen that the time of diffusion was only six hours at the most so that the observation range was a limited one. Also, from theoretical considerations of similarity, and dimensional analysis, one expects σ^2 to vary as t^2, t^3 and t for increasing time. Hence it is not clear for just what range of time the t^3 law may be expected to be valid. In addition, the theory predicts, from dimensional considerations, that σ^2 varies with the energy dissipation, E, as $E^{2/3}$ for small time and E for the intermediate times when the t^3 law holds. Hence a regular variation of E with scale may account for some changes in σ^2 with time, although no data were found to support this idea.

The validity of the t^3 law depends on the existence of an "inertial sub-range" of eddies in which the energy of the largest eddies is dissipated by transfer to progressively smaller eddies until it is finally dissipated into heat by molecular viscosity. Hence the temporal and spatial range of

these eddies will determine the range of validity of the t^3 law for the time dependence of σ^2. Also, it is not clear what effect permanent and transient local oceanographic conditions have on the diffusion of dye or radioisotopes, but certainly winds, waves, currents and the degree of density stratification play important roles, as do distance from shore, water depth, bottom topography and even experimental techniques. In Figures 6-9, sixteen different experimental determinations of σ^2 versus t are shown along with lines based on the t^3 law, determined from Brooks's equations with $\alpha = 0.02$, 0.01 and 0.005 (cgs units). The lines are seen to give good agreement in most cases, and thus, for point sources, the line:

$$\sigma^2 = .025t^3 \text{ (cgs units)}$$

does seem to give an upper bound for the σ^2 values, so that it may be used to predict conservatively the spread of sewage fields with time if the source area is small. The lower bound of the σ^2-t curve would give an upper bound for the concentration at the center of a diffusing patch since the concentration there is inversely proportional to σ^2.

C. Variation of Dye Patch Area with Time

For the radial diffusion from an instantaneous point source in the ocean, we may write (after Okubo (1962)):

$$c(r,t) = \frac{M}{4\pi\beta^3 t^3} e^{-r^2/\beta^3 t^3} \quad \text{(Obukhov, Brooks),} \tag{32}$$

$$c(r,t) = \frac{M}{2\pi P^2 t^2} e^{-r/Pt} \quad \text{(Joseph and Sendner),} \tag{33}$$

$$c(r,t) = \frac{M}{\pi\omega^2 t^2} e^{-r^2/\omega^2 t^2} \quad \text{(Okubo and Pritchard),} \tag{34}$$

or

$$c(r,t) = \frac{M}{(3/4)\pi^{3/2}\alpha^3 t^2} e^{-(r^{4/3}/\alpha^2 t^2)} \quad \text{(Okubo-new).} \tag{35}$$

For the dye patch area, A, in the case of a circular patch,

$$A = \pi r^2,$$

or $$r = \sqrt{\frac{A}{\pi}}$$

For the area of an elongated patch, we may use an equivalent radius, r_e, defined as

$$r_e = \sqrt{\frac{A}{\pi}} \ . \qquad (36)$$

From theory, we expect that the area of a dye patch, or more correctly, the area in which the concentration exceeds a certain threshold concentration (either visible or detectable), c', should be given by

$$A = \pi \beta^3 t^3 \ln \left(\frac{M}{4\pi \beta^3 t^3 c'}\right) \qquad \text{(Obukhov, Brooks)}, \qquad (37)$$

$$A = \pi P^2 t^2 \ln \left(\frac{M}{2\pi P^2 t^2 c'}\right) \qquad \text{(Joseph and Sendner)}, \qquad (38)$$

$$A = \pi \alpha^2 t^2 \ln \left(\frac{M}{\pi \alpha^2 t^2 c'}\right) \qquad \text{(Okubo and Pritchard)}, \qquad (39)$$

or $$A = \pi \left[\alpha^2 t^2 \ln \left(\frac{M}{\frac{3}{2}\pi^{3/2} \alpha^3 t^3}\right)\right]^{3/2} \qquad \text{(Okubo-new)}. \qquad (40)$$

Thus the area should vary with time, neglecting the log term, as t^3, t^2, t^2 and t^3, respectively. The effect of the log term is to make the area equal to zero at a time given by setting the terms in parenthesis equal to 1. This is another way of saying that the whole patch will be diluted below any given concentration for large enough times, under the assumed conditions. The minimum concentration, however, is ultimately determined by the amount of new water coming into the area.

The variation of area with time is shown in Figure 5. One difficulty in drawing such a general curve is that not all investigators measured the same threshold concentration, c'. Another difficulty is that the value M is not the same for more than a few data points and hence the value of A, even for the same time and same value of c', will be different. Thus the data collected are not of a character to permit a meaningful area-time curve to be drawn and are certainly not sufficient to enable any conclusions concerning the validity of certain theoretical distributions to be drawn.

D. Variation of Concentration with Time (Radial Diffusion)

For an instantaneous point-source release, the theories discussed in Section C predict that the concentration at the center of the patch, i.e., the maximum concentration, will vary inversely as the square or cube of the time of radial diffusion, depending on which theory is applied.

For a continuous point source in a current (one-dimensional diffusion), the center-line concentration varies as the $(-3/2)$ power of the distance from the source, according to Brooks's equation, if the validity of the "four-thirds law" is assumed.

There were considerable experimental data available for the change of maximum concentration with time, but due to a lack of given initial conditions on many of the data, no general curve could be plotted and hence the results are represented by many individual plots. Where possible the Brooks equation was compared with the observed data. In these comparisons the initial depth of the dye or radioisotope patch was assumed to be one centimeter, since data of this nature were usually not given. The effect of an initial depth greater than one centimeter would be to shift the theoretical curve to the left and thus to bring it into better agreement with the observed data (without changing the slope).

In Figures 10-15, where the given data were sufficient for a comparison with Brooks's equations, it is seen that the data are generally of slope (-3) as predicted by the $c \sim t^{-3}$ theory and that, when adjusted for an assumed initial depth, the Brooks curves can be made to fit the data rather well.

Figures 16 and 17 are results from a continuous point source release and are fitted with curves of slope (-3/2) as predicted from Brooks's theory. The agreement is seen to be quite good.

Figures 18-25 show data with not enough initial conditions given to enable a comparison with theory. They are fitted with lines of t^{-3}, t^{-2} or $t^{-3/2}$, whichever are better. It can be seen that for Figures 16-19 the t^{-3} curve provides a good fit, whereas in Figure 23 the $t^{-3/2}$ curve fits the data better. In the other figures the data scatter makes it hard to judge which line fits the data better.

Okubo (1965) and Carter and Okubo (1965) have proposed a theory whereby the effects of shear are taken into account, although the diffusivity is assumed constant. This model predicts $c \sim t^{-1.5}$ for short times and $t^{-2.5}$ for large times for three-dimensional ocean diffusion and $c \sim t^{-2.0}$ for the two-dimensional case. Carter and Okubo (1965) found reasonably good agreement with their theory for a few measurements off Cape Canaveral, Florida.

In general the data seem to indicate that the concentration varies inversely as time cubed, although there is considerable data scatter in many cases. The effects of local oceanographic conditions, as mentioned above, may have been significant in causing deviations from the t^{-3} law for radial diffusion from a point source.

E. Variation of Concentration with Distance (One-Dimensional Diffusion in a Current)

For a continuous source in a current, Brooks's theory predicts $c \sim x^{-3/2}$, where x is measured along the current. Figures 26-31 show good agreement with this power law, despite considerable data scatter in several cases.

Figure 32 is the data from the spread of dye introduced at a sewage treatment plant. The marked deviation from any $x^{-3/2}$ law up to distances on the order of one kilometer deserves consideration. In its report the Hancock Foundation (1965) showed that Gifford's fluctuating plume dispersion model could be extended to the case of continuous release from a volume source and used this result to derive an equation

$$c_{max}(x) = \frac{c_o}{\left[\frac{2\bar{\sigma}_y^2(x)}{\bar{\sigma}_y^2(0)} + 1\right]^{1/2}}$$

for the decrease of concentration with increasing distance along the axis of diffusion, and

$$c_o = \frac{Q/\bar{d}}{\bar{U}\sqrt{\pi}\,\bar{\sigma}_y(0)},$$

where c_o is the initial central concentration in weight per unit volume, Q is the steady discharge rate in weight per unit time, $\bar{d}$ is the average depth of the waste field, and $\bar{\sigma}_y(0)$ is the standard deviation of the initial lateral waste concentration distribution.

With the known initial values the Hancock Foundation fitted the above equation to Figure 32 with excellent agreement up to the limit of the data (about 3 kilometers). Further studies should be made to indicate the actual applicability of this extended Gifford model. It may be that the factors which cause dye patches to diffuse according to the above-mentioned laws do not affect sewage waste fields except at large distances from the outlet point, a fact of great practical significance.

F. Variation of Concentration with Dye Patch Area

The variation of concentration with dye patch area or the equivalent radius $r_e = \sqrt{\frac{A}{\pi}}$ for fixed times can be used to determine the characteristic parameters for a given theoretical distribution of concentration with time and radius. Due to time limitations, this aspect of the data-reduction was not pursued.

However, Figures 33-45 do show that for large areas the concentration decreases proportionately as the area increases, i.e.

$$\frac{c}{c_o} = \frac{A_o}{A},$$

and thus the curves of c versus r_e should show a slope of -2 on log-log paper as most do for the larger radii in a given set of observations. Hence for an equivalent radius greater than 1 kilometer (10^5 cm) the concentration in most cases for smaller areas within the patch may be estimated by using the above dilution formula.

VII. CONCLUSIONS AND RECOMMENDATIONS

The ultimate aim of this study has been to provide some verification of existing guidelines for the placement of sewage outfalls in nearshore areas.

It was seen that a fairly complete collection of recent oceanographic data related to the problem of ocean diffusion provided reasonably good verification for Brooks's formulas. In addition, several existing theoretical models have been compared with many oceanographic data by Okubo (1962) and the reader is referred there for detailed comparisons of the existing theories. It should be noted that Okubo does show that the Obukhov solution, which is equivalent to Brooks's, fits a wide range of oceanographic data and in particular excellently describes the change of concentration with radius, which this report did not have time to discuss.

The "four-thirds law" was seen to be valid in the ocean, within a reasonable degree of accuracy. The variation of σ^2 was seen to be about t^3 and that of the concentration about t^{-3} as predicted for the two-dimensional diffusion from an instantaneous point-source, with the "four-thirds law" assumed valid. The predicted variation of concentration for a continuous source ($c \sim x^{-3/2}$) was also verified approximately.

Hence it may be concluded that the effect of the scale of the turbulence is probably an important effect in determining the behavior of diffusants in the ocean. It should be noted that Brooks's formulas have been used in designing many ocean outfalls along the California coast and the performance of these outfalls as expected is perhaps a good test of the validity of the equations and assumptions involved.

Some interesting problems were touched on in the reviewed literature and many interesting qualitative observations of dye-patch diffusion were discussed there. Some of these are the elongation of a dye patch in the direction of the current by shear forces due to vertical velocity variations, the clockwise curvature of a dye patch ("Eckman spiral") in shallow waters in the Northern Hemisphere, the striation of the leading edges of a diffusing patch, the meandering of the center of gravity of a flow of dye from a continuous source, the wind stress on the surface causing waves and turbulence and thereby affecting the diffusion of a pollutant, the effect of

the current as an advective mechanism and as a cause of horizontal shear stresses, the irregular shape of any dye patch which indicates large anisotropy in the ocean and the vertical diffusion which is usually inhibited by the normal density stratification present in the ocean.

Since the purpose of this study was to aid in designing and building sewage outfalls, the reader is referred to Brooks and Koh (1965) and Fan (1967), for a description of the rise of a buoyant sewage plume in the ocean and to Hyperion Engineers (1957), Burchett, et al. (1967) and Brooks (1956) (1960) (1966), for a description of the design of outfall diffusers and the placement of the outfall. Of course any particular design must be based also on a detailed oceanographic study of any potential location for an ocean outfall. For descriptions of some methods of performing these studies the reader is referred to Brooks (1960), Carter, et al. (1967), Gunnerson (1959) (1961), Hancock Foundation (1965), Harremoes (1966), Hyperion Engineers (1957), Lawrance (1962), Oakley and Dyer (1966), Rance (1966) and Thomas (1962).

The very important problem of radioactive waste disposal is discussed by Bowles, et al. (1958), Gordon (1959), Japanese Governmental Agencies (1958), Miyake and Saruhashi (1959), National Academy of Sciences - National Research Council (1959a) (1959b), Pritchard (1959) and Seligman (1955).

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IX. APPENDIX - DATA USED FOR FIGURES

TABLE A-1

Relationship of Eddy Diffusivity, K, to Scale, L

Reported in	$K(cm^2/sec)$	$L(cm)$	Attributed To
Alsaffar (1956)	7.90×10^0	5.50×10^1	Alsaffar
	1.58×10^1	9.45×10^1	
	1.77×10^1	8.85×10^1	
	2.79×10^1	1.22×10^2	
	3.44×10^1	1.34×10^2	
Bourret and Broida (1960)	4.4×10^2	2.74×10^3	Bourret and Broida
	7.3×10^2	5.56×10^3	
	3.9×10^2	5.92×10^3	
	1.7×10^2	6.92×10^3	
Bowden (1962)	9×10^2	5.0×10^3	Olson
	2×10^4	4.0×10^4	
	7×10^4	1.5×10^5	
	2×10^5	1.5×10^5	
	7×10^5	8.5×10^5	Platania
	2×10^6	1.5×10^6	Ichiye-nearshore
	6×10^6	1.8×10^6	
	1.5×10^7	3×10^6	
	1.0×10^7	4×10^6	
	1.5×10^7	4×10^6	
	2.0×10^7	6×10^6	
	2.5×10^7	6×10^6	
	5×10^7	1.0×10^7	Ichiye-offshore
	1.3×10^8	1.8×10^7	
	3×10^8	3.0×10^7	
	5×10^8	5.0×10^7	

Reported in	K(cm^2/sec)	L(cm)	Attributed To
Csanady (1963)	1.3×10^2	7.8×10^2	Csanady
	1.2×10^2	4.2×10^2	
	4.3×10^2	9.0×10^2	
	3.0×10^2	1.2×10^3	
	1.2×10^3	1.2×10^3	
	1.2×10^2	5.0×10^2	
	5.4×10^2	2.0×10^3	
	3.2×10^2	8.2×10^2	
	5.0×10^2	1.1×10^3	
	3.0×10^2	1.1×10^3	
	4.0×10^2	1.1×10^3	
	4.7×10^2	1.1×10^3	
Gunnerson (1959)	4.87×10^2	5.7×10^4	Gunnerson-1958
	1.67×10^3	1.3×10^4	
	1.74×10^2	2.7×10^3	
	4.02×10^2	4.6×10^3	
	7.29×10^2	9.5×10^3	
	7.35×10^2	9.9×10^3	
	1.1×10^4	6.0×10^4	Gunnerson, 1959-61
	2.7×10^4	2.2×10^5	
	2.2×10^5	1.3×10^6	
	3×10^5	1.3×10^6	
	5×10^5	5×10^6	
	6×10^5	5.5×10^6	
	1.7×10^5	5×10^5	Munk
	1.2×10^5	8×10^5	
	1.4×10^5	9×10^5	

Reported in	K(cm^2/sec)	L(cm)	Attributed To
Hancock Foundation (1965)	1.21×10^3	3.6×10^3	Hancock Foundation,
	3.03×10^2	5.6×10^3	Calc. from Fig. 12
	5.11×10^3	1.12×10^4	
	5.11×10^3	2.72×10^4	
	1.67×10^3	3.68×10^4	
	1.67×10^3	3.92×10^4	
	1.92×10^5	1.8×10^4	Hancock Foundation,
	5.73×10^4	1.35×10^4	Calc. from Fig. 32
	2.29×10^3	1.17×10^4	
	6.65×10^4	7.7×10^3	
	8.18×10^4	5.1×10^3	
Ichiye and Olson (1960)	1.0×10^6	9×10^5	Joseph & Sendner
	1.8×10^6	1.5×10^6	
	3×10^5	5×10^5	Ichiye and Olson
	2×10^5	3×10^5	
	1.1×10^5	2.5×10^5	
	6×10^4	8×10^4	
	4.5×10^2	2×10^3	
	4×10^2	2.5×10^3	
	1.2×10^3	3×10^3	
	7×10^2	4.5×10^3	
	1.2×10^3	4.6×10^3	
	8×10^2	5.0×10^3	
	6×10^2	6.2×10^3	
	2×10^3	6.3×10^3	
	1.2×10^3	8×10^3	
	2.8×10^3	8×10^3	
	1.5×10^3	1×10^4	
	3.2×10^3	1.2×10^4	

Reported in	$K(cm^2/sec)$	$L(cm)$	Attributed To
Okubo (1962)	1.89×10^8	1.53×10^8	Miyake & Saruhashi
	5.28×10^8	4.76×10^8	
	9.50×10^8	9.78×10^8	
	2.17×10^7	3.17×10^7	Folsom and Vine
	5.72×10^6	1.16×10^7	Joseph & Sendner
	1.11×10^6	8.6×10^5	Ches. Bay Inst. (1960)
	2.08×10^5	3.56×10^5	Seligman
	1.8×10^5	6.4×10^5	Munk, et al.
	1.2×10^5	9.2×10^5	
	1.5×10^5	8.4×10^5	
	3.1×10^5	8.7×10^5	Ches. Bay Inst. (1962)
	2.04×10^3	1.28×10^4	Okubo, et al.
	2.43×10^3	2.15×10^4	
	2.73×10^3	3.1×10^4	
	4×10^2	2.3×10^3	Sverdup
	3.26×10^2	3.46×10^3	Gunnerson, 1956-I
	2.95×10^2	3.22×10^3	
	1.49×10^3	1.15×10^4	
	2.78×10^3	1.88×10^4	
	3.19×10^3	2.1×10^4	
	4.80×10^3	2.9×10^4	
	5.0×10^3	3.0×10^4	
	2.96×10^2	2.7×10^3	Gunnerson, 1956-II
	2.96×10^2	2.7×10^3	
	4.5×10^2	3.9×10^3	
	3.42×10^2	3.1×10^3	
	1.37×10^3	9.8×10^3	
	2.3×10^3	1.51×10^4	

Reported in	$K(cm^2/sec)$	L(cm)	Attributed To
Orlob (1961)	4.65×10^{-1}	6.1×10^{0}	Orlob #1,
	4.65×10^{-1}	6.1×10^{0}	S = .00327,
	4.65×10^{-1}	6.1×10^{0}	1" mesh
	6.5×10^{-1}	9.15×10^{0}	
	9.3×10^{-1}	9.15×10^{0}	
	9.3×10^{-1}	1.22×10^{1}	
	1.14×10^{0}	1.53×10^{1}	
	1.86×10^{0}	2.14×10^{1}	
	2.79×10^{0}	2.75×10^{1}	
	5.59×10^{0}	3.05×10^{1}	
	8.37×10^{0}	6.1×10^{1}	
	4.65×10^{-1}	3.05×10^{0}	Orlob #2,
	9.3×10^{-1}	6.1×10^{0}	S = .00055,
	1.14×10^{0}	9.15×10^{0}	1" mesh
	2.32×10^{0}	1.23×10^{1}	
	2.79×10^{0}	2.14×10^{1}	
	2.79×10^{0}	2.14×10^{1}	
	3.72×10^{0}	2.75×10^{1}	
	9.3×10^{-1}	3.05×10^{1}	
	5.59×10^{3}	3.35×10^{4}	Moon
	1.02×10^{4}	3.66×10^{4}	
	4.65×10^{0}	6.1×10^{0}	Harleman
Parker (1961)	1.34×10^{5}	2.08×10^{4}	Parker
	8.37×10^{3}	4.57×10^{3}	
	2.32×10^{4}	7.0×10^{3}	
	6.50×10^{3}	4.35×10^{3}	
	1.21×10^{3}	1.59×10^{3}	
	4.65×10^{2}	3.05×10^{4}	Munk et al.
	4.65×10^{7}	9.15×10^{6}	
	4.2×10^{1}	3.05×10^{3}	Burke
	3.0×10^{2}	3.05×10^{3}	
	3.0×10^{2}	3.05×10^{3}	

Reported in	$K(cm^2/sec)$	$L(cm)$	Attributed To
	2.4×10^2	3.05×10^3	
	6.9×10^2	3.05×10^3	
	6.3×10^2	3.05×10^3	
	8.4×10^1	7×10^3	
	6.0×10^2	7×10^3	
	6.0×10^2	7×10^3	
	4.8×10^2	7×10^3	
	1.38×10^3	7×10^3	
	1.26×10^3	7×10^3	
Pearson (1956)	1.5×10^9	1×10^9	Hidaka
	2×10^7	3×10^7	Hanzawa
	3×10^6	1×10^7	
	1×10^6	1×10^6	Proudman
	1.5×10^5	3×10^5	Munk
	5×10^2	1×10^3	
	1.8×10^4	5×10^4	von Arx
	7×10^3	5×10^4	
	5×10^7	1×10^8	Sverdup #1
	1×10^4	4×10^4	
	1.5×10^0	4×10^1	Sverdup #2
	3×10^0	9×10^1	
	1×10^1	1×10^2	
	6×10^1	2.5×10^2	
	4×10^2	1×10^3	
	3×10^2	3×10^3	
	8×10^2	4×10^3	
	1.4×10^3	1.5×10^4	
	1.6×10^3	7×10^3	
	1×10^4	3.5×10^4	
	1.9×10^3	1.07×10^4	Ketchum
	2.5×10^3	1.65×10^4	
	6.8×10^3	2.25×10^4	
	4×10^8	1×10^8	Neumann-Sverdup

Reported in	$K(cm^2/sec)$	$L(cm)$	Attributed To
Stommel (1949)	8.43×10^1	1.88×10^2	Richardson & Stommel
	6.4×10^0	2.67×10^1	
	2.4×10^3	9.0×10^3	Stommel
	1.2×10^2	1.8×10^3	
	5.0×10^1	2.9×10^2	
	9.2×10^1	4.3×10^2	
	1.04×10^1	7.7×10^1	
	3.37×10^2	7.95×10^2	
	3.6×10^1	1.03×10^2	
Waldichuk (1966)	4.5×10^4	7×10^3	Waldichuk

TABLE A-2

Symbols Used in Figure 3

Symbol	Reported In	Data Attributed To
	Alsaffar (1956)	Alsaffar
	Bourret and Broida (1960)	Bourret and Broida
	Bowden (1962)	Olson
		Platania
		Ichiye - nearshore
		Ichiye - offshore
	Csanady (1963)	Csanady
	Gunnerson (1959)	Gunnerson - 1958
		Gunnerson, 1959-61
		Munk
	Hancock Foundation (1965)	Hancock Foundation, Fig. 12
		Hancock Foundation, Fig. 32
	Ichiye and Olson (1960)	Joseph and Sendner
		Ichiye and Olson
	Okubo (1962)	Miyake and Saruhashi
		Folsom and Vine
		Joseph and Sendner
		Ches. Bay Inst. (1960)
		Seligman
		Munk, et al.
		Ches. Bay Inst. (1962)

Symbol	Reported In	Data Attributed To
		Okubo, et al.
		Sverdup
		Gunnerson, 1956 - I
		Gunnerson, 1956 - II
	Orlob (1961)	Orlob #1
		Orlob #2
		Moon
		Harleman
	Parker (1961)	Parker
		Munk, et al.
		Burke
	Pearson (1956)	Hidaka
		Hanzawa
		Proudman
		Munk, et al.
		von Arx
		Sverdup #1
		Sverdup #2
		Ketchum
		Neumann-Sverdup
	Stommel (1949)	Richardson and Stommel
		Stommel
	Waldichuk (1956)	Waldichuk

TABLE A-3

Relationship of Mean Square Dispersion, σ^2,
to Time of Diffusion, t.

Reported In	σ^2, cm^2	t, sec	Attributed to
Bourret and Broida (1960)	2.5×10^5	1×10^0	Bourret and Broida
	1.1×10^6	9.6×10^2	
	2.5×10^6	1.92×10^3	
	3.25×10^6	2.88×10^3	
	4.3×10^6	3.78×10^3	
Carter and Okubo (1965)	7.5×10^8	7.6×10^4	Carter and Okubo
	4.23×10^9	2.56×10^5	
	1.21×10^{10}	2.69×10^5	
	8.3×10^9	2.84×10^5	
	1.42×10^{10}	3.56×10^5	
	4.5×10^{10}	1.97×10^5	
	3.25×10^9	1.12×10^5	
	3.36×10^9	1.12×10^5	
	5.1×10^9	1.816×10^5	
	1.21×10^{10}	1.816×10^5	
	4.5×10^{10}	2.66×10^5	
	2.37×10^{10}	1.852×10^5	
	1.12×10^{10}	1.655×10^5	
	1.56×10^8	2.29×10^5	
	3.43×10^8	1.1×10^5	
	1.025×10^9	1.975×10^5	
Hancock Foundation (1965)	4×10^7	4.45×10^3	Hancock Foundation Fig. 32 cont. source
	3.26×10^7	5.35×10^3	
	1.12×10^7	3.56×10^3	
	8.65×10^6	2.89×10^3	
	8.55×10^6	2.22×10^3	
	3.72×10^6	1.11×10^3	
	3.82×10^5	4.89×10^2	

Reported In	σ^2, cm^2	t, sec	Attributed to
	4.65×10^5	6×10^2	Hancock Foundation Fig. 12 inst. source
	1.395×10^6	9.6×10^2	
	2.23×10^6	2.4×10^3	
	1.67×10^7	3.66×10^3	
	8.93×10^7	9.6×10^3	
	7.62×10^7	1.44×10^4	
	1.02×10^8	1.8×10^4	
Ichiye, et al. (1964)	5.5×10^9	1.2×10^5	Ichiye, et al., Bahama Banks
	4.5×10^9	9.6×10^4	
	3.15×10^8	7.8×10^4	
	2×10^7	1.8×10^4	
	1.45×10^7	1.14×10^4	
	5×10^8	1.86×10^5	
	4.5×10^8	1.74×10^5	
	3.5×10^8	1.14×10^5	
	2.5×10^8	9.6×10^4	
	1.5×10^8	7.8×10^4	
	2.6×10^7	1.44×10^4	
	7×10^9	9×10^4	Ichiye, et al., off N. J.
	6.5×10^9	8.4×10^4	
	3×10^9	7.2×10^4	
	4×10^8	4.62×10^4	
	3.5×10^8	4.2×10^4	
	3.5×10^8	3.54×10^4	
	4.5×10^9	1.68×10^4	
	7×10^8	1.26×10^4	
	2×10^8	1.14×10^4	
	1.35×10^8	8.4×10^3	
	2.05×10^8	2.52×10^4	
	1.6×10^8	1.86×10^4	
	1.05×10^8	1.38×10^4	
	2.05×10^8	1.14×10^4	
	1.05×10^8	6.6×10^3	

Reported In	σ^2, cm^2	t, sec	Attributed to
Okubo (1962)	1.46×10^{15}	5×10^{6}	Miyake and Saruhashi
	1.43×10^{16}	2.2×10^{7}	
	5.98×10^{16}	3.7×10^{7}	
	6.28×10^{13}	3.46×10^{6}	Folsom and Vine
	4.66×10^{10}	6.3×10^{4}	Ches. Bay Inst. (1960)
	7.9×10^{9}	4.51×10^{4}	Seligman
	1.32×10^{10}	8.64×10^{4}	Munk, et al.
	4.4×10^{10}	1.73×10^{5}	
	6.33×10^{10}	2.59×10^{5}	
	4.77×10^{10}	1.85×10^{5}	Ches. Bay Inst. (1962)
	7.5×10^{5}	1.8×10^{3}	Gunnerson (1956)-I
	6.46×10^{5}	3.6×10^{3}	
	8.21×10^{5}	6.9×10^{3}	
	2.21×10^{7}	7.2×10^{3}	
	2.75×10^{7}	7.9×10^{3}	
	5.24×10^{7}	1.08×10^{4}	
	5.60×10^{7}	1.2×10^{4}	
	4.76×10^{5}	1.2×10^{3}	Gunnerson (1956)-II
	4.76×10^{5}	1.8×10^{3}	
	9.52×10^{5}	2.4×10^{3}	
	6.04×10^{5}	3.0×10^{3}	
	6.01×10^{6}	3.6×10^{3}	
	1.43×10^{7}	4.8×10^{3}	
	9.1×10^{6}	2.4×10^{3}	Okubo, et al.
	2.88×10^{7}	7.18×10^{3}	
	5.98×10^{7}	1.09×10^{4}	

TABLE A-4

Symbols Used in Figure 4

Symbol	Reported In	Data Attributed To
◈	Bourret and Broida (1960)	Bourret and Broida
×	Carter and Okubo (1965)	Carter and Okubo
⛉	Hancock Foundation (1965)	Hancock Foundation, Fig. 32
⊙		Hancock Foundation, Fig. 12
⊞	Ichiye, et al. (1964)	Ichiye, et al., Bahama Banks
⊕		Ichiye, et al., Off N. J.
+	Okubo (1962)	Miyake and Saruhashi
●		Folsom and Vine
⊕		Ches. Bay Inst. (1960)
◎		Seligman
▽		Munk, et al.
△		Ches. Bay Inst. (1962)
⊙		Gunnerson (1956) - I
⊡		Gunnerson (1956) - II
▯		Okubo, et al.

TABLE A-5

Relationship of Dye Path Area, A, and Time, t.

Reported In	A, cm^2	t, sec	Attributed To
Carter and Okubo (1965)	6.37×10^{9}	7.6×10^{4}	Carter and Okubo
	3.8×10^{10}	2.56×10^{5}	
	1.13×10^{11}	2.69×10^{5}	
	7.38×10^{10}	2.84×10^{5}	
	1.07×10^{11}	3.56×10^{5}	
	1.43×10^{11}	1.97×10^{5}	
	4.6×10^{10}	1.12×10^{5}	
	3.39×10^{10}	1.12×10^{5}	
	1.05×10^{11}	1.816×10^{5}	
	1.84×10^{11}	1.816×10^{5}	
	3.14×10^{11}	2.66×10^{5}	
	2.23×10^{11}	1.852×10^{5}	
	1.17×10^{11}	1.655×10^{5}	
	4.96×10^{11}	2.29×10^{5}	
	1.11×10^{10}	8.79×10^{4}	
	2.32×10^{10}	1.1×10^{5}	
	3.52×10^{10}	1.975×10^{5}	
Costin (1965)	2.59×10^{9}	2.52×10^{4}	Costin
	6.72×10^{9}	2.52×10^{4}	
	1.29×10^{10}	3.6×10^{4}	
	3.89×10^{10}	9×10^{4}	
	3.11×10^{10}	9×10^{4}	
	2.59×10^{11}	1.8×10^{5}	
	5.18×10^{10}	1.8×10^{5}	

Reported In	A, cm^2		t, sec		Attributed To
Fukuda, et al. (1964)	3	$\times 10^7$	6	$\times 10^2$	Fukuda, et al. (Offshore)
	9.5	$\times 10^7$	2.3	$\times 10^3$	
	2.4	$\times 10^8$	4.5	$\times 10^3$	
	4.2	$\times 10^8$	6.3	$\times 10^3$	
	7.4	$\times 10^8$	9.9	$\times 10^3$	
	9.1	$\times 10^8$	1.2	$\times 10^4$	
	1.65	$\times 10^9$	1.6	$\times 10^4$	
	1.7	$\times 10^9$	1.9	$\times 10^4$	
	1.9	$\times 10^9$	2	$\times 10^4$	
	2.5	$\times 10^9$	2.3	$\times 10^4$	
	3.3	$\times 10^7$	6	$\times 10^2$	
	1.0	$\times 10^8$	2.3	$\times 10^3$	
	4.6	$\times 10^8$	4.5	$\times 10^3$	
	6.3	$\times 10^8$	6.3	$\times 10^3$	
	9.8	$\times 10^8$	9.9	$\times 10^3$	
	1.1	$\times 10^9$	1.2	$\times 10^4$	
	2.1	$\times 10^9$	1.6	$\times 10^4$	
	1.9	$\times 10^8$	1.9	$\times 10^4$	
	2.7	$\times 10^9$	2.0	$\times 10^4$	
	2.6	$\times 10^9$	2.3	$\times 10^4$	
	1.8	$\times 10^6$	2.4	$\times 10^2$	
	2.6	$\times 10^6$	3.6	$\times 10^2$	
	6.3	$\times 10^6$	5.4	$\times 10^2$	
	6.8	$\times 10^7$	1.9	$\times 10^3$	
	6.9	$\times 10^7$	2.4	$\times 10^3$	
	3.2	$\times 10^8$	6.9	$\times 10^3$	
	2.7	$\times 10^6$	1.8	$\times 10^2$	
	5.6	$\times 10^7$	2.2	$\times 10^3$	
	1.6	$\times 10^8$	3.8	$\times 10^3$	
	3.7	$\times 10^8$	5.7	$\times 10^3$	
	1.0	$\times 10^9$	9.9	$\times 10^3$	
	1.3	$\times 10^9$	1.1	$\times 10^4$	
	2.1	$\times 10^9$	1.2	$\times 10^4$	

Reported In	A, cm^2	t, sec	Attributed To
	2.4×10^9	1.8×10^4	
	3.8×10^7	9×10^2	
	1.0×10^8	3.1×10^3	
	1.8×10^8	5.1×10^3	
	1.1×10^9	1.2×10^4	
	9.4×10^7	5.1×10^2	Fukuda, et al. (Onshore)
	1.4×10^8	1.0×10^3	
	2.6×10^8	2.4×10^3	
	4.6×10^8	2.9×10^3	
	3.1×10^8	3.4×10^3	
	4.1×10^8	4.0×10^3	
	6.9×10^8	6.0×10^3	
	1.7×10^9	1.0×10^4	
	1.8×10^9	1.0×10^4	
	1.7×10^7	2×10^2	
	9.5×10^7	5×10^2	
	1.2×10^8	1×10^3	
	1.3×10^8	2×10^3	
	1.1×10^6	2×10^2	
	4.5×10^6	5×10^2	
	1.1×10^7	1×10^3	
	9.2×10^7	2×10^3	
	1.9×10^8	3×10^3	
	7.1×10^6	1.2×10^2	
	1.5×10^7	4.2×10^2	
	6.4×10^7	7.2×10^2	
	1.2×10^8	1.0×10^3	
	1.5×10^8	1.3×10^3	
	3.7×10^8	1.9×10^3	
	2.4×10^6	1.8×10^2	
	8.7×10^6	5.4×10^2	
	2.6×10^7	9×10^2	
	6.3×10^7	1.2×10^3	

Reported In	A, cm^2	t, sec	Attributed To
	9.4×10^7	1.7×10^3	
	1.2×10^8	1.9×10^3	
	1.6×10^8	2.2×10^3	
	2.0×10^8	2.6×10^3	
	1.9×10^8	2.9×10^3	
	2.1×10^8	3.4×10^3	
	2.6×10^8	3.7×10^3	
	3.6×10^8	4.1×10^3	
	3.9×10^8	4.4×10^3	
	4.8×10^8	5×10^3	
Hancock Foundation (1965)	8.95×10^7	1.8×10^3	Hancock Foundation
	1.12×10^8	3.78×10^3	
Japanese Governmental Agencies (1958)	1.256×10^8	7.2×10^2	Jap. Govt. Agencies
	3.77×10^8	2.4×10^3	
	8.8×10^8	6.24×10^3	
	1.78×10^9	1.092×10^4	
	3.22×10^9	1.512×10^4	
Joseph and Sendner (1958)	4×10^{14}	3.45×10^6	Folsom and Vine
Joseph, et al. (1964)	6.36×10^{10}	7.6×10^4	Joseph, et al.
	2.016×10^{11}	1.73×10^5	
	5.452×10^{11}	2.49×10^5	
	1.647×10^{10}	6.99×10^4	
	3.239×10^{10}	9.65×10^4	
	1.41×10^{11}	1.59×10^5	
	2.776×10^{11}	2.47×10^5	
	1.82×10^{11}	2.39×10^5	
	2.405×10^{11}	4.09×10^5	

Reported In	A, cm^2	t, sec	Attributed To
Miyake and Saruhashi(1959)	2.49×10^{16}	5.18×10^{6}	Miyake and Saruhashi
	1.39×10^{17}	2.33×10^{7}	
	3.22×10^{17}	3.62×10^{7}	
Okubo (1962)	1.575×10^{11}	1.84×10^{5}	Ches. Bay Inst. (1962)
	2.93×10^{11}	6.3×10^{4}	Ches. Bay Inst. (1960)
	8.3×10^{10}	8.64×10^{4}	Munk, et al.
	2.76×10^{11}	1.73×10^{5}	
	3.98×10^{11}	2.59×10^{5}	
	4.7×10^{6}	1.8×10^{3}	Gunnerson (1956)-I
	4.05×10^{6}	3.6×10^{3}	
	5.16×10^{7}	6.9×10^{3}	
	1.39×16^{8}	7.2×10^{3}	
	1.73×10^{8}	7.9×10^{3}	
	3.28×10^{8}	1.08×10^{4}	
	3.51×10^{8}	1.2×10^{4}	
	2.99×10^{6}	1.2×10^{3}	Gunnerson (1956)-II
	2.99×10^{6}	1.8×10^{3}	
	5.98×10^{6}	2.4×10^{3}	
	3.78×10^{6}	3.0×10^{3}	
	3.78×10^{7}	3.6×10^{3}	
	8.97×10^{8}	4.8×10^{3}	
	5.71×10^{7}	2.4×10^{3}	Okubo, et al.
	1.81×10^{8}	7.18×10^{3}	
	3.75×10^{8}	1.09×10^{4}	
Seligman (1955)	1.03×10^{9}	1.17×10^{4}	Seligman
	9.4×10^{9}	2.53×10^{4}	
	1.23×10^{10}	4.44×10^{4}	
	1.25×10^{10}	5.55×10^{4}	

Reported In	A, cm^2	t, sec	Attributed To
Waldichuk (1966)	2.81×10^8	1.74×10^3	Waldichuk
	3.08×10^8	1.74×10^3	
	2.65×10^9	1.74×10^3	
	5.35×10^8	1.71×10^3	
	3.19×10^8	1.71×10^3	
	4.39×10^8	1.74×10^3	
	2.81×10^8	1.74×10^3	
	2.94×10^8	1.8×10^3	
	1.84×10^8	1.8×10^3	
	4.01×10^8	1.86×10^3	
	4.58×10^8	1.86×10^3	
	1.77×10^8	1.86×10^3	
	5.23×10^8	1.86×10^3	
	4.26×10^8	1.86×10^3	
	2.56×10^8	1.8×10^3	
	6.69×10^9	1.8×10^3	
	3.89×10^8	1.8×10^3	
	2.18×10^8	1.8×10^3	
	2.34×10^8	1.8×10^3	
	1.69×10^9	1.74×10^3	
	3.54×10^8	1.74×10^3	
	1.17×10^9	1.65×10^3	
	3.85×10^8	1.65×10^3	
	2.01×10^8	1.65×10^3	
	1.08×10^9	1.62×10^3	
	9.1×10^8	1.62×10^3	

TABLE A-6

Symbols Used in Figure 5

Symbol	Reported In	Data Attributed To
△	Carter and Okubo (1965)	Carter and Okubo
◇	Costin (1965)	Costin
⊙	Fukuda, et al. (1964)	Fukuda, et al. (Offshore)
⊡		Fukuda, et al. (Onshore)
■	Hancock Foundation (1965)	Hancock Foundation
⍜	Japanese Governmental Agencies (1952)	Jap. Govt. Agencies
X	Joseph and Sendner (1958)	Folsom and Vine
◎	Joseph, et al. (1964)	Joseph, et al.
⊞	Miyake and Saruhashi (1959)	Miyake and Saruhashi
+	Okubo (1962)	Ches. Bay Inst. (1962)
●		Ches. Bay Inst. (1960)
▮		Munk, et al.
⊙		Gunnerson (1956) - I
▲		Gunnerson (1956) - II
▼		Okubo, et al.
⊕	Seligman (1955)	Seligman
▽	Waldichuk (1966)	Waldichuk

TABLE A-7

Relationship of Concentration, C, with Time, t.

Reported In	C	Time (sec)	Attributed to
Carter and Okubo (1965)	C_{max}(ppb)		Carter and Okubo -
	36	3.42×10^4	Release 1
	.65	1.05×10^5	
	.45	1.85×10^5	
	.30	2.69×10^5	
	2.8	1.41×10^5	2
	1.2	1.66×10^5	
	.34	2.29×10^5	
	2.1	2.41×10^4	3
	7.3	7.6×10^4	
	4.4	1.65×10^5	
	1.0	2.56×10^5	
	2900	4.68×10^3	4
	1900	6.48×10^3	
	310	2.38×10^4	
	.69	2.69×10^5	
	.73	2.84×10^5	
	.34	3.59×10^5	
	3300	3.6×10^3	5
	2200	5.4×10^3	
	1500	7.2×10^3	
	900	1.01×10^4	
	11.6	9×10^4	
	2.4	1.15×10^5	
	.70	1.97×10^5	
	2000	5.4×10^3	6
	600	1.04×10^4	
	9.6	9.35×10^4	
	8.4	9.35×10^4	

Reported In	$\frac{C}{C_{max}(ppb)}$	Time (sec)	Attributed To
	6.5	1.12×10^5	
	6.0	1.14×10^5	
	2.5	1.13×10^5	
	3.0	1.85×10^5	
	.88	1.88×10^5	
	.33	2.66×10^5	
	33	1.33×10^3	7
	15	2.45×10^3	
	5	3.17×10^3	
	7.1	4.21×10^3	
	2.0	1.1×10^4	
	29	2.34×10^3	11
	38	3.13×10^3	
	20	6.26×10^3	
	12	1.08×10^4	
	9.6	1.3×10^4	
	6.4	1.47×10^4	
	4.6	1.58×10^4	
	4.7	1.69×10^4	
	127	1.41×10^4	8
	68	2.44×10^4	
	35	8.77×10^4	
	24	1.1×10^5	
	7.1	1.9×10^5	
	5.6	1.97×10^5	
	3.1	3.47×10^5	
	.54	6.16×10^5	
	.36	7.91×10^5	
	.29	9.55×10^5	
	93	1.74×10^4	9
	127	9.08×10^4	
	116	9.35×10^4	

Reported In	C / C_{max} (ppb)	Time (sec)	Attributed To
	39	1.87×10^5	
	10	3.47×10^5	
	8.9	3.56×10^5	
	2.4	5.2×10^5	
	1.9	7.01×10^5	
	1.8	8.7×10^5	
	1.2	1.14×10^6	
	72	1×10^5	10
	13	1.73×10^5	
	9.5	1.83×10^5	
	8.9	1.84×10^5	
	5.2	2.7×10^5	
	3.9	3.49×10^5	
	3.4	3.62×10^5	
	.96	6.05×10^5	
	.93	6.19×10^5	
	.50	7.93×10^5	
	.35	9.59×10^5	
Carter, et al. (1967)	C_{max}		Carter, et al.
	7×10^3	2.28×10^3	$C_o = 10^5$
	4.3×10^3	2.34×10^3	
	3.8×10^3	6.55×10^3	
	2.9×10^3	6.72×10^3	
	1.7×10^3	1.175×10^4	
	1.2×10^3	1.18×10^4	
	6×10^2	1.75×10^4	
	5×10^2	1.76×10^4	

Reported In		Time (sec)	Attributed To
Csanady (1963)	C_{max} (g/cm^3)		
	1.35×10^{-7}	2.26×10^{3}	Csanady
	1.6×10^{-7}	2.35×10^{3}	$C_o = 10^{-1}$, $\dot{m} = .2$ g sec
	1.32×10^{-7}	2.74×10^{3}	
	1.49×10^{-7}	2.93×10^{3}	
	1.65×10^{-7}	3.17×10^{3}	
	1.37×10^{-7}	3.29×10^{3}	
	1.83×10^{-7}	3.41×10^{3}	
	7.1×10^{-8}	5.24×10^{3}	
	9.15×10^{-8}	5.73×10^{3}	
Gunnerson (1959)	C_{max} C_o		Lawrance and Miller
	.667	3.6×10^{3}	
	.500	7.2×10^{3}	
	.400	1.08×10^{4}	
	.286	1.44×10^{4}	
	.167	2.16×10^{4}	
Hancock Foundation (1965)	C_{max} (ppm)		Hancock Foundation,
	6	5.4×10^{2}	Fig. 3; M = 5 lb.
	5	5.1×10^{2}	
	4.5	6.3×10^{2}	
	3.5	6.3×10^{2}	
	3.2	9×10^{2}	
	1.7	9.6×10^{2}	
	1.7	1.02×10^{3}	
	0.9	1.2×10^{3}	
	0.46	1.8×10^{3}	
	.35	2.1×10^{3}	
	.31	2.4×10^{3}	
	.28	2.1×10^{3}	
	.25	2.1×10^{3}	

Reported In	C_{max}(ppm)	Time (sec)	Attributed To
	.25	3.6×10^3	
	.20	4.2×10^3	
	.17	2.4×10^3	
	.15	3.0×10^3	
	.12	3.9×10^3	
	.11	4.2×10^3	
	.10	6.6×10^3	
	.099	4.8×10^3	
	.099	5.4×10^3	
	.085	5.88×10^3	
	.080	5.88×10^3	
	.045	6.0×10^3	
	.025	9×10^3	
	.021	7.8×10^3	
	.020	7.8×10^3	
	.019	8.4×10^3	
	.015	9.0×10^3	
	10	6.6×10^2	Fig. 14; M = 5 lb.
	5	1.08×10^3	
	1	1.92×10^3	
	.25	2.94×10^3	
	.08	5.4×10^3	
	.068	9.0×10^3	
	.064	9.6×10^3	
	.050	1.02×10^4	
	.023	1.5×10^4	
	.018	1.74×10^4	
	.019	1.86×10^4	
	.010	1.86×10^4	

Reported In	C_{max}(ppm)	Time (sec) $t(=\frac{x}{u})$	Attributed To
			Fig. 34, $\dot{m}$ = 6.1 lb/hr U = 0.27 kts.
	.34	1.18×10^3	
	.30	1.62×10^3	
	.35	1.8×10^3	
	.22	2.02×10^3	
	.18	2.89×10^3	
	.17	2.78×10^3	
	.16	4.22×10^3	
	.15	3.78×10^3	
	.12	4.22×10^3	
	.12	4.67×10^3	
	.12	4.89×10^3	
	.11	3.11×10^3	
	.10	4.44×10^3	
	.092	5.33×10^3	
	.089	5.33×10^3	
	.068	6.89×10^3	
	.062	7.56×10^3	
	.061	7.33×10^3	
	.053	1.067×10^4	
	.24	5.33×10^3	Fig. 36; $\dot{m}$ = 6.1 lb/hr U = .14 kts
	.19	8.44×10^3	
	.13	8.44×10^3	
	.12	1.02×10^4	
	.11	9.33×10^3	
	.094	1.29×10^4	
	.091	1.56×10^4	
	.073	1.78×10^4	
	.073	1.96×10^4	
	.063	2.18×10^4	
	.050	1.38×10^4	
	.039	1.78×10^4	
	.031	2.67×10^4	
	.026	3.24×10^4	
	.022	3.51×10^4	
	.021	3.91×10^4	

Reported In		Time (sec)	Attributed To
	C_{max}(ppb)	$t(=\frac{x}{u})$	Fig. 41; $\dot{m}$ = 42 lb/hr U = .32 kts
	240	1.88×10^{0}	
	250	1.88×10^{0}	
	210	4.52×10^{1}	
	210	6.41×10^{1}	
	180	6.41×10^{1}	
	190	7.35×10^{1}	
	130	1.36×10^{2}	
	130	1.56×10^{2}	
	110	3.58×10^{2}	
	94	1.11×10^{3}	
	80	1.47×10^{3}	
	80	1.88×10^{3}	
	70	2.07×10^{3}	
	60	2.45×10^{3}	
	63	3.58×10^{3}	
	51	4.14×10^{3}	
	49	4.71×10^{3}	
	50	6.03×10^{3}	
	42	6.22×10^{3}	
	38	6.97×10^{3}	
	33	7.72×10^{3}	
	30	7.72×10^{3}	
	32	1.13×10^{4}	
	30	1.21×10^{4}	
	27	1.37×10^{4}	
	20	1.70×10^{4}	

Reported In	C_{max} (g/cm^3)	T (sec)	Attributed To
Joseph, et al. (1964)	4×10^{-8}	7.6×10^{4}	Joseph, et al.
	5×10^{-9}	1.73×10^{5}	M = 450 kg.
	1.2×10^{-9}	2.49×10^{5}	
	9×10^{-9}	6.99×10^{4}	M = 175 kg.
	7×10^{-9}	9.65×10^{4}	
	1.5×10^{-9}	1.59×10^{5}	
	7×10^{-10}	2.47×10^{5}	
	2.5×10^{-9}	2.38×10^{5}	M = 350 kg.
	7.5×10^{-10}	4.09×10^{5}	
Noble (1961)	1.1×10^{-6}	1.8×10^{2}	Noble: $C_o = 10^{-3}$ (approx.)
	5×10^{-7}	6×10^{2}	Initial Patch Radius = 10^4 cm (approx.)
	1.5×10^{-7}	1.5×10^{3}	
	5×10^{-8}	2.4×10^{3}	
	3×10^{-9}	3.6×10^{3}	
	1.2×10^{-9}	5.4×10^{3}	
	2.5×10^{-10}	6.6×10^{3}	
	1.7×10^{-10}	7.5×10^{3}	
	3×10^{-11}	8.4×10^{3}	
	4×10^{-12}	9.6×10^{3}	
	1.1×10^{-12}	1.08×10^{4}	
	C_{max}/C_o		
Okubo (1962)	5×10^{-9}	7.2×10^{3}	Seligman
	1×10^{-9}	7.2×10^{3}	
	7×10^{-10}	9×10^{3}	
	2×10^{-10}	4.8×10^{4}	
	1×10^{-10}	6.0×10^{4}	

Reported In	C_{max}/C_o		Time (sec)		Attributed To
	5	$\times 10^{-5}$	2.4	$\times 10^{3}$	Okubo, et al.
	3	$\times 10^{-6}$	6	$\times 10^{3}$	
	1	$\times 10^{-6}$	7.2	$\times 10^{3}$	
	1	$\times 10^{-7}$	7.8	$\times 10^{3}$	
	C_{max} (ppb)				
	33		4	$\times 10^{4}$	Ches. Bay Inst. (1962)
	.50		1.9	$\times 10^{5}$	
	.43		1.9	$\times 10^{5}$	
	.23		2.8	$\times 10^{5}$	
Pritchard and Carpenter (1960)	$\frac{C}{M} \cdot D(cm^{-2})$				Pritchard and Carpenter
	2	$\times 10^{-10}$	1	$\times 10^{5}$	Fig. 11
	1	$\times 10^{-10}$	1.2	$\times 10^{5}$	
	2	$\times 10^{-11}$	2	$\times 10^{5}$	
	4	$\times 10^{-10}$	6	$\times 10^{4}$	Fig. 12
	2.4	$\times 10^{-10}$	8	$\times 10^{4}$	
	6.5	$\times 10^{-11}$	1.3	$\times 10^{5}$	
	5.5	$\times 10^{-11}$	1.5	$\times 10^{5}$	
	3.5	$\times 10^{-11}$	2	$\times 10^{5}$	
	2.0	$\times 10^{-11}$	2.1	$\times 10^{5}$	
	1.9	$\times 10^{-11}$	2.3	$\times 10^{5}$	
	1.7	$\times 10^{-11}$	4	$\times 10^{5}$	
	1.9	$\times 10^{-11}$	4	$\times 10^{5}$	Fig. 12
	8	$\times 10^{-12}$	4.5	$\times 10^{5}$	
	7	$\times 10^{-12}$	5.5	$\times 10^{5}$	

Reported In		Time (sec)	Attributed To
Seligman (1955)	$\frac{C_{max}}{C_o}$		Seligman
	1×10^{-4}	$10^1 - 10^2$	
	6×10^{-6}	$7.2 \times 10^3 - 1.08 \times 10^4$	
	1×10^{-6}	3.24×10^4	
	5×10^{-7}	4.32×10^4	
	4×10^{-7}	5.40×10^4	
Thomas (1962)	C_{max} (activity)		Thomas
	1.3×10^1	1×10^3	$C_o = 10^8$
	4×10^1	1.5×10^3	
	2.8×10^1	1.6×10^3	
	1.05×10^2	2×10^3	
	2.6×10^1	2×10^3	
	3.7×10^1	2.2×10^3	
	2.1×10^1	2.3×10^3	
	1.3×10^1	2.6×10^3	
	3.3×10^0	2.9×10^3	
	3.6×10^1	2.9×10^3	
	2.0×10^1	3.0×10^3	
	5.2×10^0	3.9×10^3	
	1.1×10^{-1}	5.0×10^3	
	1.3×10^1	5.1×10^3	
	5.2×10^1	5.9×10^3	
	1.8×10^0	6.0×10^3	
	6.3×10^{-1}	7.2×10^3	
	7.1×10^{-1}	8.0×10^3	
	1.0×10^0	3.3×10^3	
Waldichuk (1966)	C/C_o - average	T - average	Waldichuk
	.093	1.8×10^3	

Reported In	$C(g/cm^3)$	Time (sec)	Attributed To
Okubo (1962)	7×10^{-9}	6.0×10^{2}	Noble
	2×10^{-9}	1.8×10^{3}	
	6×10^{-10}	2.4×10^{3}	
	3×10^{-11}	4.8×10^{3}	
	1×10^{-11}	6.0×10^{3}	
	2×10^{-12}	6.3×10^{3}	
	2×10^{-12}	6.6×10^{3}	
	2×10^{-13}	6.6×10^{3}	

TABLE A-8

Relationship of Concentration, C, with Longitudinal Distance, x.

Data From	C $C(g/cm^3)$		x(cm)		Attributed To
Csanady (1963)	1.35	$\times 10^{-7}$	5.65	$\times 10^{4}$	Csanady
	1.6	$\times 10^{-7}$	5.9	$\times 10^{4}$	
	1.33	$\times 10^{-7}$	6.85	$\times 10^{4}$	
	1.49	$\times 10^{-7}$	7.32	$\times 10^{4}$	
	1.65	$\times 10^{-7}$	7.93	$\times 10^{4}$	
	1.37	$\times 10^{-7}$	8.23	$\times 10^{4}$	
	1.83	$\times 10^{-7}$	8.55	$\times 10^{4}$	
	7.09	$\times 10^{-8}$	1.31	$\times 10^{5}$	
	9.15	$\times 10^{-8}$	1.43	$\times 10^{5}$	
Fukuda, et al. (1964)	C/Q				Fukuda, et al., Fig. 8
	1.5	$\times 10^{-5}$	3	$\times 10^{3}$	Dye Experiments
	3.1	$\times 10^{-5}$	3	$\times 10^{3}$	
	1.2	$\times 10^{-5}$	4.8	$\times 10^{3}$	
	1.6	$\times 10^{-5}$	4.9	$\times 10^{3}$	
	2	$\times 10^{-5}$	6.9	$\times 10^{3}$	
	6.3	$\times 10^{-6}$	7	$\times 10^{3}$	
	1.9	$\times 10^{-5}$	9	$\times 10^{3}$	
	2	$\times 10^{-6}$	9.3	$\times 10^{3}$	
	5	$\times 10^{-6}$	9.3	$\times 10^{3}$	
	5.3	$\times 10^{-6}$	9.7	$\times 10^{3}$	
	6	$\times 10^{-6}$	9.7	$\times 10^{3}$	
	1.3	$\times 10^{-5}$	9.9	$\times 10^{3}$	
	2	$\times 10^{-5}$	1	$\times 10^{4}$	
	9.1	$\times 10^{-6}$	1.1	$\times 10^{4}$	
	6.9	$\times 10^{-6}$	1.2	$\times 10^{4}$	
	5.9	$\times 10^{-6}$	1.3	$\times 10^{4}$	
	9.2	$\times 10^{-6}$	1.6	$\times 10^{4}$	
	4.1	$\times 10^{-6}$	1.6	$\times 10^{4}$	

Data From	C/Q	x(cm)	Attributed To
	4.3×10^{-6}	1.9×10^{4}	
	1×10^{-6}	2×10^{4}	
	5.8×10^{-6}	2×10^{4}	
	3×10^{-6}	2.0×10^{4}	
	3.2×10^{-6}	2.1×10^{4}	
	2.2×10^{-6}	2.3×10^{4}	
	5×10^{-6}	2.8×10^{4}	
	1.3×10^{-6}	2.9×10^{4}	
	1.5×10^{-6}	2.9×10^{4}	
	4×10^{-6}	2.9×10^{4}	
	4.5×10^{-6}	2.9×10^{4}	
	5.1×10^{-6}	3×10^{4}	
	9×10^{-6}	3×10^{4}	
	5.1×10^{-6}	3.2×10^{4}	
	1.6×10^{-6}	3.8×10^{4}	
	3.3×10^{-6}	3.8×10^{4}	
	1.3×10^{-6}	3.9×10^{4}	
	2.5×10^{-6}	3.9×10^{4}	
	1.1×10^{-6}	4.0×10^{4}	
	1.1×10^{-6}	4.1×10^{4}	
	2×10^{-6}	4.3×10^{4}	
	2.5×10^{-6}	4.3×10^{4}	
	8.2×10^{-7}	4.8×10^{4}	
	1.2×10^{-6}	5.1×10^{4}	
	6.5×10^{-6}	6.1×10^{4}	
	1.2×10^{-6}	7.0×10^{4}	
	2.8×10^{-6}	8.0×10^{4}	
	1×10^{-6}	8.5×10^{4}	
	2.7×10^{-6}	5×10^{4}	Kuji River Data
	1.2×10^{-7}	1×10^{5}	
	9×10^{-8}	1.3×10^{5}	
	1.1×10^{-7}	2×10^{5}	
	2.8×10^{-7}	2×10^{5}	
	3×10^{-7}	2×10^{5}	
	3.2×10^{-7}	2×10^{5}	

Data From	C/Q	x(cm)	Attributed To
	5×10^{-7}	2×10^{5}	
	5.3×10^{-7}	2×10^{5}	
	9×10^{-8}	4×10^{5}	
	2×10^{-7}	4×10^{5}	
	4×10^{-7}	4×10^{5}	
	4.2×10^{-7}	4×10^{5}	
	5×10^{-7}	4×10^{5}	
	6×10^{-7}	4×10^{5}	
	1.8×10^{-7}	5×10^{5}	
	4.1×10^{-7}	5×10^{5}	
	5×10^{-7}	5×10^{5}	
	3.9×10^{-7}	7×10^{5}	
	3.3×10^{-7}	8.5×10^{5}	
	8×10^{-8}	9×10^{5}	
	1.0×10^{-7}	9×10^{5}	
	1.6×10^{-7}	9×10^{5}	
	2.3×10^{-7}	9×10^{5}	

Data From	C_{max}(ppm)		Attributed To
Hancock Foundation (1965)	.34	1.615×10^{4}	Hancock Foundation; Fig. 34; $\dot{m}$ = 6.1 lb/hr
	.30	2.22×10^{4}	
	.35	2.47×10^{4}	
	.22	2.77×10^{4}	
	.18	3.97×10^{4}	
	.17	3.81×10^{4}	
	.16	5.8×10^{4}	
	.15	5.19×10^{4}	
	.12	5.8×10^{4}	
	.12	6.4×10^{4}	
	.12	6.71×10^{4}	
	.11	4.27×10^{4}	
	.10	6.1×10^{4}	
	.092	7.32×10^{4}	

Data From	C_{max}(ppm)	x(cm)	Attributed To
	.089	7.32×10^4	
	.068	9.45×10^4	
	.062	1.04×10^5	
	.061	1.01×10^5	
	.053	2.3×10^5	
	.24	3.66×10^4	Fig. 36, $\dot{m}$ = 6.1 lb/hr
	.19	5.8×10^4	
	.13	5.8×10^4	
	.12	7.01×10^4	
	.11	6.41×10^4	
	.094	8.85×10^4	
	.091	1.07×10^5	
	.073	1.22×10^5	
	.073	1.34×10^5	
	.063	1.5×10^5	
	.050	9.45×10^4	
	.039	1.22×10^5	
	.031	1.83×10^5	
	.026	2.23×10^5	
	.022	2.41×10^5	
	.021	2.68×10^5	
C_{max}(ppb)	240	3.05×10^1	Fig. 41; $\dot{m}$ = 42 lb/hr
	250	3.05×10^1	
	210	7.32×10^2	
	210	1.04×10^3	
	180	1.04×10^3	
	190	1.19×10^3	
	130	2.19×10^3	
	130	2.53×10^3	
	110	5.8×10^3	
	94	1.8×10^4	
	80	2.68×10^4	
	80	3.05×10^4	
	70	3.35×10^4	

Data From	C_{max}(ppb)	x(cm)	Attributed To
	60	3.96×10^4	
	63	5.8×10^4	
	51	6.7×10^4	
	49	7.62×10^4	
	50	9.75×10^4	
	42	1.01×10^5	
	38	1.13×10^5	
	33	1.25×10^5	
	30	1.25×10^5	
	32	1.83×10^5	
	30	1.95×10^5	
	27	2.22×10^5	
	20	2.74×10^5	
Hyperion Engineers (1957)	C/C_o	x(cm)	Boston Harbor Studies Table F.4
	.442	3.05×10^3	
	.961	1.525×10^4	
	.227	5.5×10^4	
	.153	8.05×10^4	
	.144	9.15×10^4	
	.250	1.81×10^5	
	.459	2.41×10^5	
	.459	3.05×10^5	
	.637	3.6×10^5	
	.158	4.03×10^5	
	.227	5.03×10^5	
	.208	4.58×10^4	Table F.5
	.250	1.07×10^5	
	.167	1.68×10^5	
	.0833	1.92×10^5	
	.0222	2.9×10^5	
	.0239	3.51×10^5	
	.0159	4.11×10^5	

Data From	C/C_o	x(cm)	Attributed To
	.204	6.1×10^3	Table F.6
	.128	7.93×10^3	
	.156	4.27×10^4	
	.152	4.64×10^4	
	.098	6.05×10^4	
	.044	6.92×10^4	
	.096	7.62×10^4	
	.039	9.15×10^4	
	.073	1.07×10^5	
	.010	1.41×10^5	
	.031	1.62×10^5	
	.179	1.8×10^5	
	.065	1.83×10^5	
	.039	1.96×10^5	
	.416	2.19×10^5	
	.116	2.62×10^5	
	.039	3.12×10^5	
	.118	3.22×10^5	
	.357	3.62×10^5	
	.098	4.43×10^5	
	.0934	4.63×10^5	
	.143	5.61×10^5	
	.110	5.85×10^5	
	.078	6.85×10^5	
	1.0	0	Table F.12
	.61	9.15×10^3	
	.437	3.05×10^4	
	.312	4.58×10^4	
	.098	9.15×10^4	

Data From	$\frac{C}{M} \cdot D$ (cm^{-2})	x(cm)	Attributed To
Pritchard and Carpenter (1960)			Pritchard and Carpenter
	2.3×10^{-4}	5×10^{3}	Fig. 13
	1.9×10^{-4}	1×10^{4}	
	2.5×10^{-5}	2×10^{4}	
	3.5×10^{-6}	5×10^{4}	
	1×10^{-6}	1.2×10^{5}	
	6×10^{-5}	2×10^{4}	Fig. 14
	3.5×10^{-5}	5×10^{4}	
	2.3×10^{-6}	1×10^{5}	
	2.0×10^{-6}	2×10^{5}	
	9×10^{-6}	3×10^{5}	
	6×10^{-6}	4×10^{5}	
	4×10^{-6}	6×10^{5}	
	2×10^{-6}	8×10^{5}	
	2×10^{-6}	1×10^{6}	
	1.8×10^{-6}	1.1×10^{6}	

TABLE A-9

Relationship of Concentration, C, with Dye Patch Radius, r.
(r = radius of circle of area equivalent to dye patch area)

Data From Carter and Okubo (1965) C(ppb)	C	r(cm)	Attributed To Carter and Okubo
	6	1.6×10^4	Release 3 -
	4	2.9×10^4	$t = 7.6 \times 10^4$ sec
	2	4.5×10^4	
	.8	1.3×10^4	$t = 2.56 \times 10^5$ sec
	.6	2.2×10^4	
	.4	6.4×10^4	
	.2	1.11×10^5	
	.6	3.6×10^4	Release 4 -
	.5	6.4×10^4	$t = 2.69 \times 10^5$ sec
	.4	9.4×10^4	
	.3	1.32×10^5	
	.2	1.67×10^5	
	.15	1.90×10^5	
	.7	2.1×10^4	$t = 2.84 \times 10^5$ sec
	.6	4.0×10^4	
	.5	6.2×10^4	
	.4	8.5×10^4	
	.3	1.15×10^5	
	.2	1.53×10^5	
	.3	5.2×10^4	$t = 3.56 \times 10^5$ sec
	.2	1.2×10^5	
	.1	1.84×10^5	
	.6	1×10^5	Release 5 -
	.5	1.67×10^5	$t = 1.97 \times 10^5$ sec
	.4	2.17×10^5	
	.3	2.77×10^5	
	.2	2.13×10^5	
	5	1.6×10^4	Release 6 -
	4	2.7×10^4	$t = 1.12 \times 10^5$ sec

Data From	$\frac{C}{C(ppb)}$	r(cm)	Attributed To
	3	4.5×10^4	
	2	6.4×10^4	
	1	1.0×10^5	
	.5	1.21×10^5	
	5	2.4×10^4	$t = 1.12 \times 10^5$ sec
	4	4.2×10^4	
	3	5.9×10^4	
	2	8.4×10^4	
	1	1.04×10^5	
	2	2.2×10^4	$t = 1.816 \times 10^5$ sec
	1	3.9×10^4	
	.8	6.1×10^4	
	.6	7.8×10^4	
	.4	1.04×10^5	
	.2	1.83×10^5	
	.6	2.6×10^4	$t = 1.816 \times 10^5$ sec
	.4	6×10^4	
	.2	1.21×10^5	
	.1	2.04×10^5	
	.05	2.42×10^5	
	.3	4.9×10^4	$t = 2.66 \times 10^5$ sec
	.2	1.67×10^5	
	.1	3.16×10^5	
	.4	4.6×10^4	Release 1 -
	.35	1.03×10^5	$t = 1.852 \times 10^5$ sec
	.30	1.37×10^5	
	.25	1.61×10^5	
	.20	1.91×10^5	
	.15	2.24×10^5	
	.10	2.66×10^5	
	1	4.5×10^4	Release 2 -
	.8	6×10^4	$t = 1.655 \times 10^5$ sec
	.6	1.14×10^5	
	.4	1.44×10^5	
	.2	1.93×10^5	

Data From	$\frac{C}{C(ppb)}$	r(cm)	Attributed To
	.3	9.8×10^4	$t = 2.29 \times 10^5$ sec
	.25	1.7×10^5	
	.2	2.34×10^5	
	.15	3.12×10^5	
	.10	3.30×10^5	
	.05	3.97×10^5	
	27	5.35×10^3	Release 8 -
	15	1.31×10^4	$t = 8.79 \times 10^4$ sec
	9	1.69×10^4	
	3	2.67×10^4	
	1.5	3.66×10^4	
	15	9.26×10^3	$t = 1.1 \times 10^5$ sec
	9	1.41×10^4	
	3	2.18×10^4	
	1.5	3.12×10^4	
	4	9.26×10^3	$t = 1.975 \times 10^5$ sec
	2	2.44×10^4	
	1.5	3.12×10^4	
	1	4.53×10^4	
	.5	5.68×10^4	
Joseph and Sendner (1958)	C/C_{max}		Folsom and Vine
	.1	1.13×10^7	$t = 3.456 \times 10^6$ sec
	.2	8.74×10^6	
	.3	6.68×10^6	
	.4	5.05×10^6	
	.6	1.60×10^6	
	.8	1.25×10^6	
	1	3.3×10^5	

Data From	$\Delta EK(m^{-1})$	C/C_{max}	r(cm)	Attributed To
	.2	.1	3.65×10^{7}	Joseph (1958)
	.3	.15	2.82×10^{7}	
	.5	.25	1.87×10^{7}	
	.75	.375	9.52×10^{6}	
	1.0	.5	1.22×10^{6}	
	.8	.3	1.9×10^{6}	Joseph (1953)
	1.0	.4	1.59×10^{6}	
	1.2	.45	1.29×10^{6}	
	1.5	.6	8.1×10^{5}	
	.6	.45	1.47×10^{6}	
	.8	.6	8.4×10^{5}	
	1.0	.75	4.6×10^{5}	

Joseph, et al. (1964)	$C(g/cm^3)$		Joseph, et al.
	4×10^{-8}	1.24×10^{4}	Trial 1; M = 450 kg
	2×10^{-8}	4×10^{4}	$t = 7.6 \times 10^{4}$ sec
	1×10^{-8}	5.01×10^{4}	
	5×10^{-9}	5.71×10^{4}	
	2.5×10^{-9}	6.86×10^{4}	
	1×10^{-9}	9×10^{4}	
	5×10^{-10}	1.158×10^{5}	
	2.5×10^{-10}	1.453×10^{5}	
	5.0×10^{-9}	4.51×10^{4}	$t = 1.73 \times 10^{5}$ sec
	2.5×10^{-9}	8.89×10^{4}	
	1×10^{-9}	1.199×10^{5}	
	5×10^{-10}	1.49×10^{5}	
	2.5×10^{-10}	1.793×10^{5}	
	1.0×10^{-10}	2.161×10^{5}	
	5×10^{-11}	2.533×10^{5}	
	1.2×10^{-9}	8.94×10^{4}	$t = 2.49 \times 10^{5}$ sec
	1×10^{-9}	1.328×10^{5}	
	9×10^{-10}	1.614×10^{5}	
	6×10^{-10}	2.056×10^{5}	

Data From	$C(g/cm^3)$	$r(cm)$	Attributed To
	4×10^{-10}	2.335×10^5	
	3×10^{-10}	2.596×10^5	
	2×10^{-10}	2.978×10^5	
	1×10^{-10}	3.558×10^5	
	5×10^{-11}	4.166×10^5	
			Trial 2; M = 175 kg
	9×10^{-9}	8.4×10^3	$t = 6.99 \times 10^4$ sec
	8×10^{-9}	1.35×10^4	
	7×10^{-9}	1.86×10^4	
	6×10^{-9}	2.45×10^4	
	5×10^{-9}	2.95×10^4	
	4×10^{-9}	3.51×10^4	
	3×10^{-9}	4.09×10^4	
	2×10^{-9}	4.92×10^4	
	1×10^{-9}	5.68×10^4	
	7.5×10^{-10}	6.16×10^4	
	5×10^{-10}	6.6×10^4	
	2.5×10^{-10}	7.24×10^4	
	7×10^{-9}	7.4×10^3	$t = 9.65 \times 10^4$ sec
	6×10^{-9}	1.26×10^4	
	5×10^{-9}	2.16×10^4	
	4×10^{-9}	3.22×10^4	
	3×10^{-9}	4.46×10^4	
	2×10^{-9}	5.52×10^4	
	1×10^{-9}	7.16×10^4	
	5×10^{-10}	8.49×10^4	
	2.5×10^{-10}	1.015×10^5	
	1.5×10^{-9}	2.62×10^4	$t = 1.6 \times 10^5$ sec
	1×10^{-9}	5.66×10^4	
	7.5×10^{-10}	7.93×10^4	
	5×10^{-10}	9.66×10^4	
	2.5×10^{-10}	1.386×10^5	
	1.5×10^{-10}	1.659×10^5	
	1.0×10^{-10}	1.864×10^5	
	5×10^{-11}	2.119×10^5	

Data From	$C(g/cm^3)$	$r(cm)$	Attributed To
	7×10^{-10}	3.6×10^{4}	$t = 2.48 \times 10^{5}$ sec
	5×10^{-10}	9.09×10^{4}	
	3.5×10^{-10}	1.236×10^{5}	
	2.5×10^{-10}	1.54×10^{5}	
	1.5×10^{-10}	1.833×10^{5}	
	1.0×10^{-10}	2.108×10^{5}	
	5×10^{-11}	2.524×10^{5}	
	2.5×10^{-11}	2.973×10^{5}	
			Trial 3; M = 350 kg
	2.5×10^{-9}	2.99×10^{4}	$t = 2.39 \times 10^{5}$ sec
	2×10^{-9}	5.18×10^{4}	
	1.5×10^{-9}	7.69×10^{4}	
	1×10^{-9}	1.123×10^{5}	
	5×10^{-10}	1.392×10^{5}	
	2.5×10^{-10}	1.686×10^{5}	
	1.5×10^{-10}	1.898×10^{5}	
	1×10^{-10}	2.041×10^{5}	
	5×10^{-11}	2.407×10^{5}	
	7.5×10^{-10}	5.71×10^{4}	$t = 4.09 \times 10^{5}$ sec
	5×10^{-10}	1.167×10^{5}	
	2.5×10^{-10}	1.672×10^{5}	
	1.5×10^{-10}	2.130×10^{5}	
	1.0×10^{-10}	2.419×10^{5}	
	5×10^{-11}	2.767×10^{5}	

Okubo (1962)	$C(g/cm^3)$		Okubo
	3.5×10^{-10}	1.025×10^{5}	$t = 1.84 \times 10^{5}$; depth = 5 ft.
	3.0×10^{-10}	1.37×10^{5}	
	2.5×10^{-10}	1.605×10^{5}	
	2.0×10^{-10}	1.914×10^{5}	
	1.5×10^{-10}	2.24×10^{5}	

Data From	C/C_{max}	r(cm)	Attributed To
Okubo (1962)	.5	1×10^4	Seligman - 6' depth of sample
	.4	3×10^4	
	.3	6×10^4	
	.2	8×10^4	
	.1	1.2×10^5	
	.5	2×10^4	12' depth of sample
	.4	3.5×10^4	
	.3	6.5×10^4	
	.2	8×10^4	
	.1	1.2×10^5	
	C(ppb)		Ches. Bay Inst. (1962)
	.33	1×10^5	
	.30	1.4×10^5	
	.23	1.7×10^5	
	.20	1.9×10^5	
	.13	2.3×10^5	
Seligman (1955)	$C(g/cm^3)$	r(cm)	Seligman - surface samples
	50×10^{-9}	1.8×10^4	$C_{max} = 137 \times 10^{-9}$
	100×10^{-9}	8.75×10^3	$t = 1.16 \times 10^4$
	5×10^{-9}	5.48×10^4	$C_{max} = 70 \times 10^{-9}$
	20×10^{-9}	4.34×10^4	$t = 2.56 \times 10^4$
	40×10^{-9}	2.66×10^4	
	60×10^{-9}	1.27×10^4	
	5×10^{-9}	5.99×10^4	$C_{max} = 25.7 \times 10^{-9}$
	10×10^{-9}	4.59×10^4	$t = 4.45 \times 10^4$
	15×10^{-9}	3.44×10^4	
	20×10^{-9}	2.4×10^4	
	25×10^{-9}	9.1×10^3	
	2×10^{-9}	6.15×10^4	$C_{max} = 17.1 \times 10^{-9}$
	5×10^{-9}	4.63×10^4	$t = 5.55 \times 10^4$
	8×10^{-9}	3.68×10^4	
	10×10^{-9}	1.31×10^4	

Data From	C_{max} (activity)	r (cm)	Attributed To
Thomas (1962)			Thomas
	3.1×10^{2}	5.65×10^{2}	$C_o \doteq 10^8$
	1.55×10^{2}	6.9×10^{2}	
	1.55×10^{2}	7.5×10^{2}	
	1.55×10^{2}	9.76×10^{2}	
	8×10^{1}	1.27×10^{3}	
	8×10^{1}	1.38×10^{3}	
	8×10^{1}	1.59×10^{3}	
	4×10^{1}	1.69×10^{3}	
	4×10^{1}	2.40×10^{3}	
	4×10^{1}	2.46×10^{3}	
	2×10^{1}	1.78×10^{3}	
	2×10^{1}	2.03×10^{3}	
	2×10^{1}	3.09×10^{3}	
	2×10^{1}	3.09×10^{3}	
	1×10^{1}	3.09×10^{3}	
	1×10^{1}	3.57×10^{3}	
	1×10^{1}	3.99×10^{3}	

X. FIGURES

Note: Figures 1 and 2 appear in the text as Page IV-6a.

Fig. 3

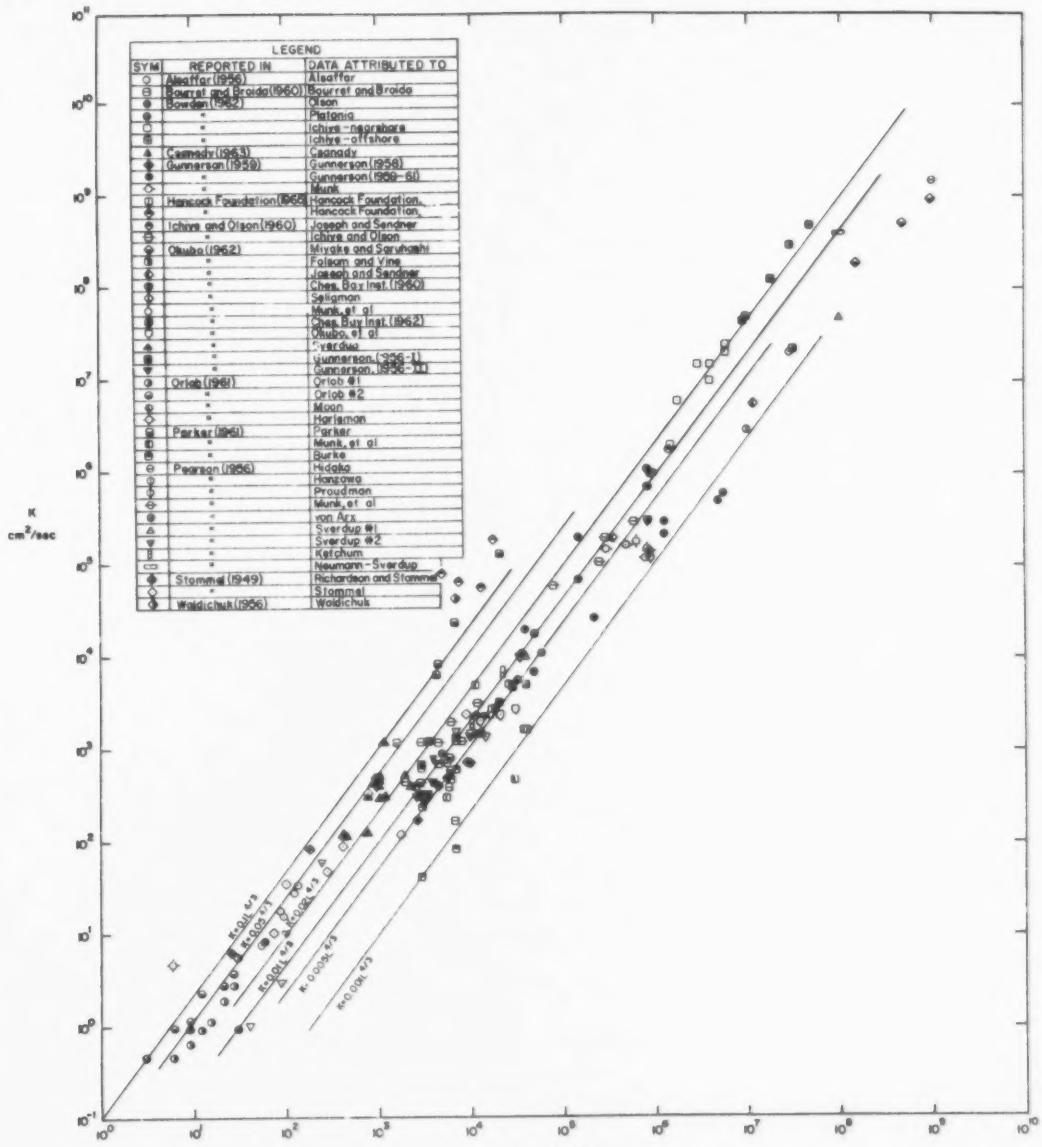

LEGEND
SYM | REPORTED IN | DATA ATTRIBUTED TO
Alaffar (1956) | Alaffar
Bowden (1962) | Olson
" | Platania
" | Ichiye - nearshore
" | Ichiye - offshore
Csanady (1963) | Csanady
Gunnerson (1959) | Gunnerson (1958)
" | Gunnerson (1959-61)
" | Munk
Hancock Foundation (1958) | Hancock Foundation
" | Hancock Foundation
Ichiye and Olson (1960) | Joseph and Sendner
" | Ichiye and Olson
Okubo (1962) | Miyake and Saruhashi
" | Folsom and Vine
" | Joseph and Sendner
" | Ches. Bay Inst. (1960)
" | Seligman
" | Munk, et al
" | Ches. Bay Inst. (1962)
" | Okubo, et al
" | Sverdup
" | Gunnerson, (1956-1)
" | Gunnerson, 1956-10)
Orlob (1961) | Orlob #1
" | Orlob #2
" | Moon
" | Harleman
Parker (1961) | Parker
" | Munk, et al
" | Burke
Pearson (1956) | Hidaka
" | Hanzawa
" | Proudman
" | Munk, et al
" | von Arx
" | Sverdup #1
" | Sverdup #2
" | Ketchum
" | Neumann - Sverdup
Stommel (1949) | Richardson and Stommel
" | Stommel
Waldichuk (1956) | Waldichuk
K cm²/sec
L cm
K=0.01L^4/3
K=0.005L^4/3
K=0.002L^4/3
K=0.0003L^4/3
K=0.01L^4/3

Fig. 4

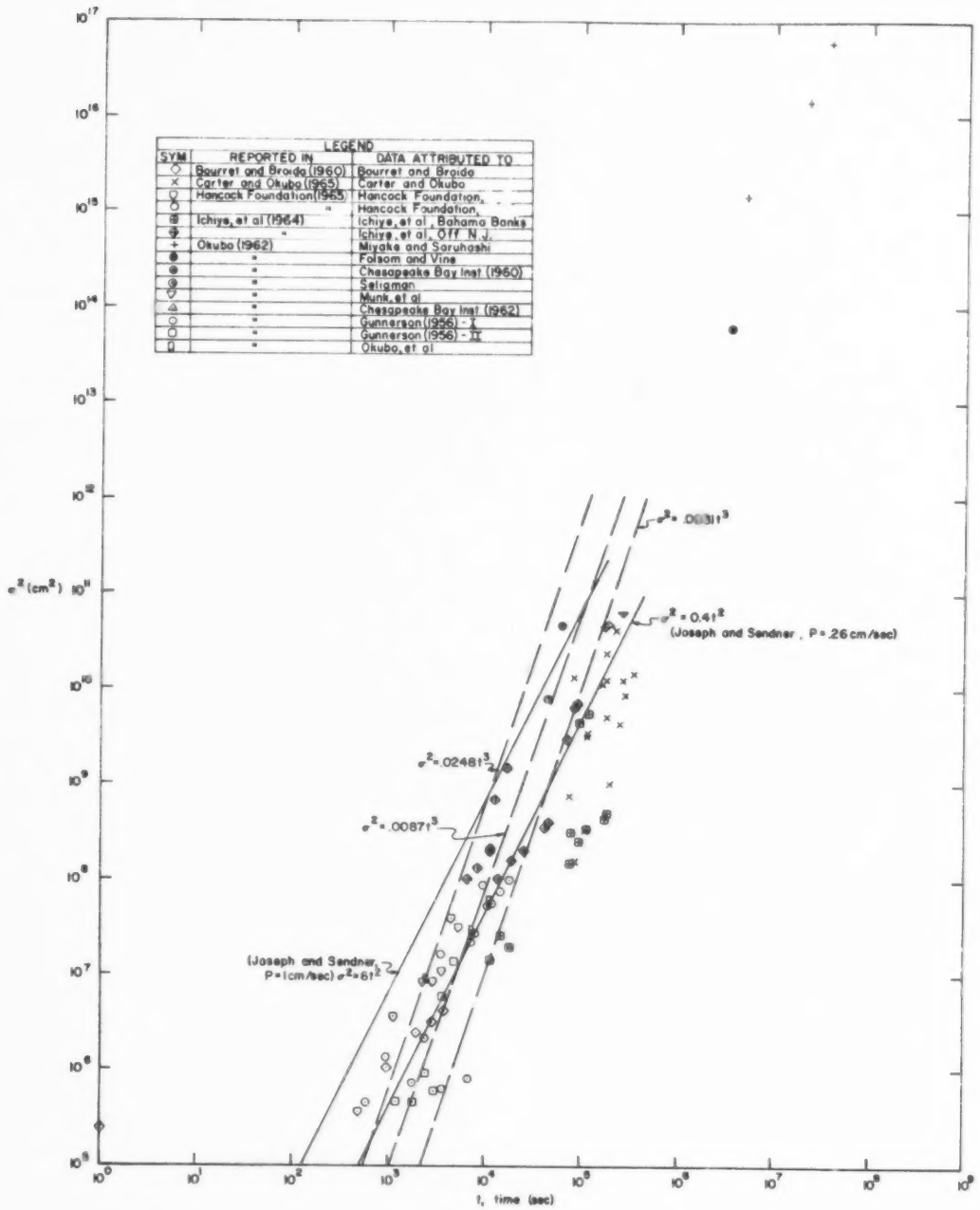
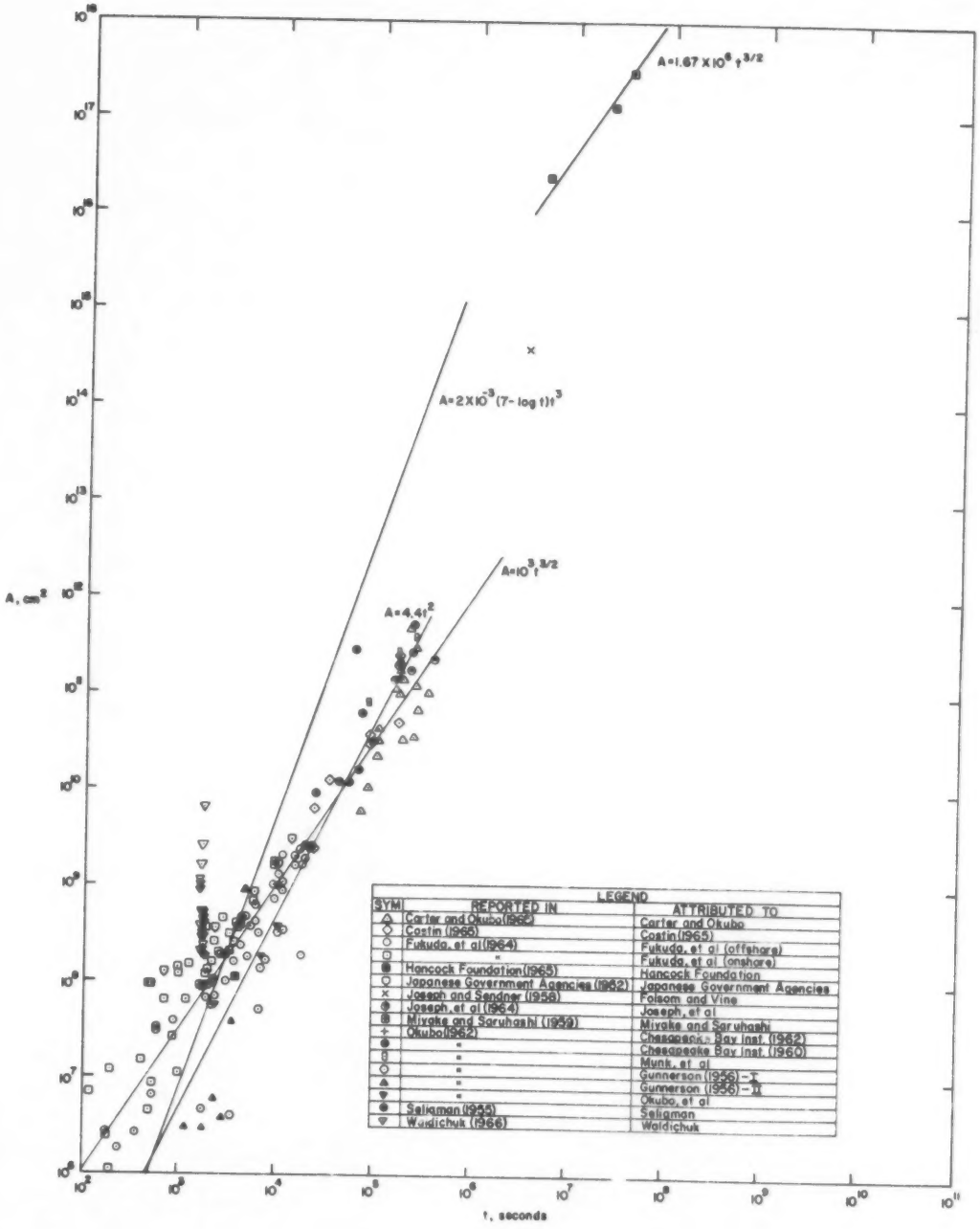

LEGEND
SYM | REPORTED IN | DATA ATTRIBUTED TO
Bourret and Broida (1960) | Bourret and Broida
Carter and Okubo (1965) | Carter and Okubo
Hancock Foundation (1965) | Hancock Foundation,
" | Hancock Foundation,
Ichiye, et al (1964) | Ichiye, et al., Bahama Banks
" | Ichiye, et al., Off N.J.
Okubo (1962) | Miyake and Saruhashi
" | Folsom and Vine
" | Chesapeake Bay Inst (1960)
" | Seligman
" | Munk, et al
" | Chesapeake Bay Inst (1962)
" | Gunnerson (1956) - I
" | Gunnerson (1956) - II
" | Okubo, et al
$\sigma^2 = .0031 t^3$
$\sigma^2 = 0.4 t^2$
(Joseph and Sendner, P = .26 cm/sec)
$\sigma^2 = .0248 t^3$
$\sigma^2 = .0087 t^3$
(Joseph and Sendner, P = 1 cm/sec) $\sigma^2 = 6 t^2$
σ^2 (cm^2)
t, time (sec)

Fig. 5


A=1.67 X 10^6 t^3/2
A=2X10^3 (7- log t) t^3
A=10^3 t^3/2
A=4.4 t^2
A, cm^2
t, seconds
LEGEND
SYM | REPORTED IN | ATTRIBUTED TO
Carter and Okubo (1962) | Carter and Okubo
Costin (1965) | Costin (1965)
Fukuda, et al (1964) | Fukuda, et al (offshore)
" | Fukuda, et al (onshore)
Hancock Foundation (1965) | Hancock Foundation
Japanese Government Agencies (1962) | Japanese Government Agencies
Joseph and Sendner (1958) | Folsom and Vine
Joseph, et al (1964) | Joseph, et al
Miyake and Saruhashi (1959) | Miyake and Saruhashi
Okubo (1962) | Chesapeake Bay Inst. (1962)
" | Chesapeake Bay Inst. (1960)
" | Munk, et al
" | Gunnerson (1956) – I
" | Gunnerson (1956) – II
" | Okubo, et al
Seligman (1955) | Seligman
Waldichuk (1966) | Waldichuk

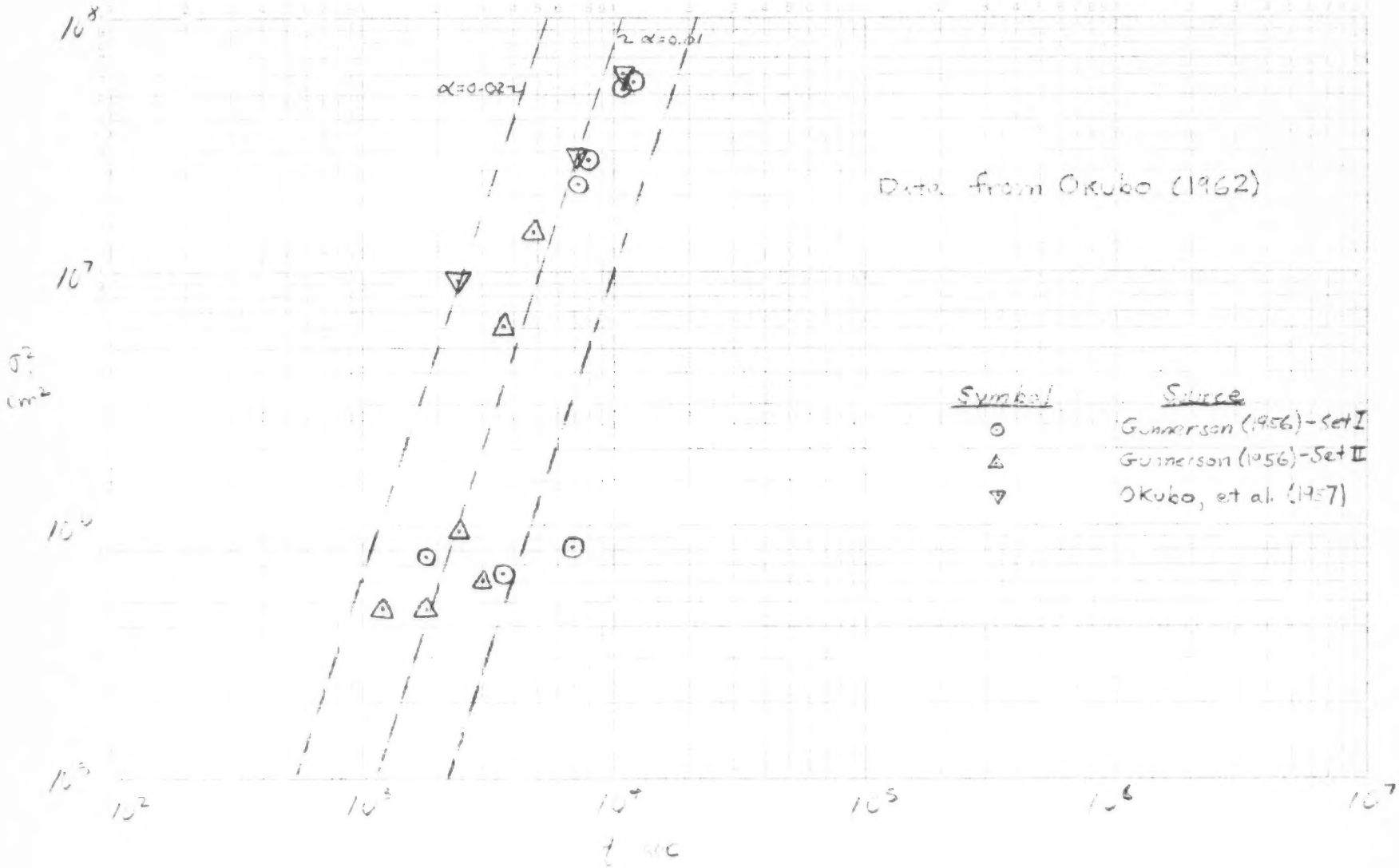

10^8
10^7
10^6
10^5
10^2
10^3
10^4
10^5
10^6
10^7
σ^2 cm^2
t sec
α=0.027
α=0.01
Data from Okubo (1962)
Symbol
Source
Gunnerson (1956) - Set I
Gunnerson (1956) - Set II
Okubo, et al. (1957)

Fig. 6

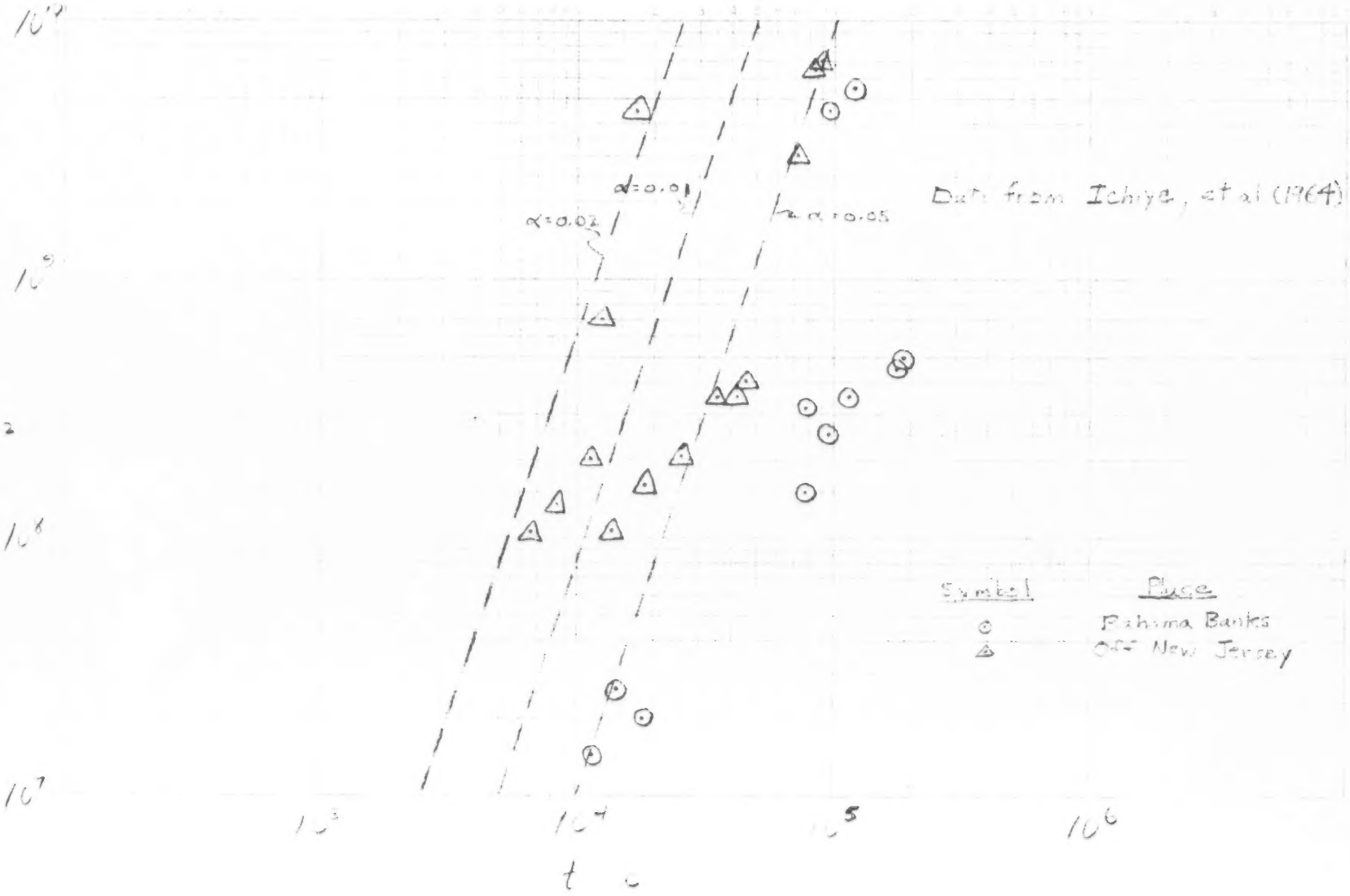

10^7
10^8
10^9
Γ^2, cm^2
α=0.01
α=0.02
α=0.05
Data from Ichiye, et al (1964)
Symbol
Place
Bahama Banks
Off New Jersey
10^3
10^4
10^5
10^6
t

Fig. 7

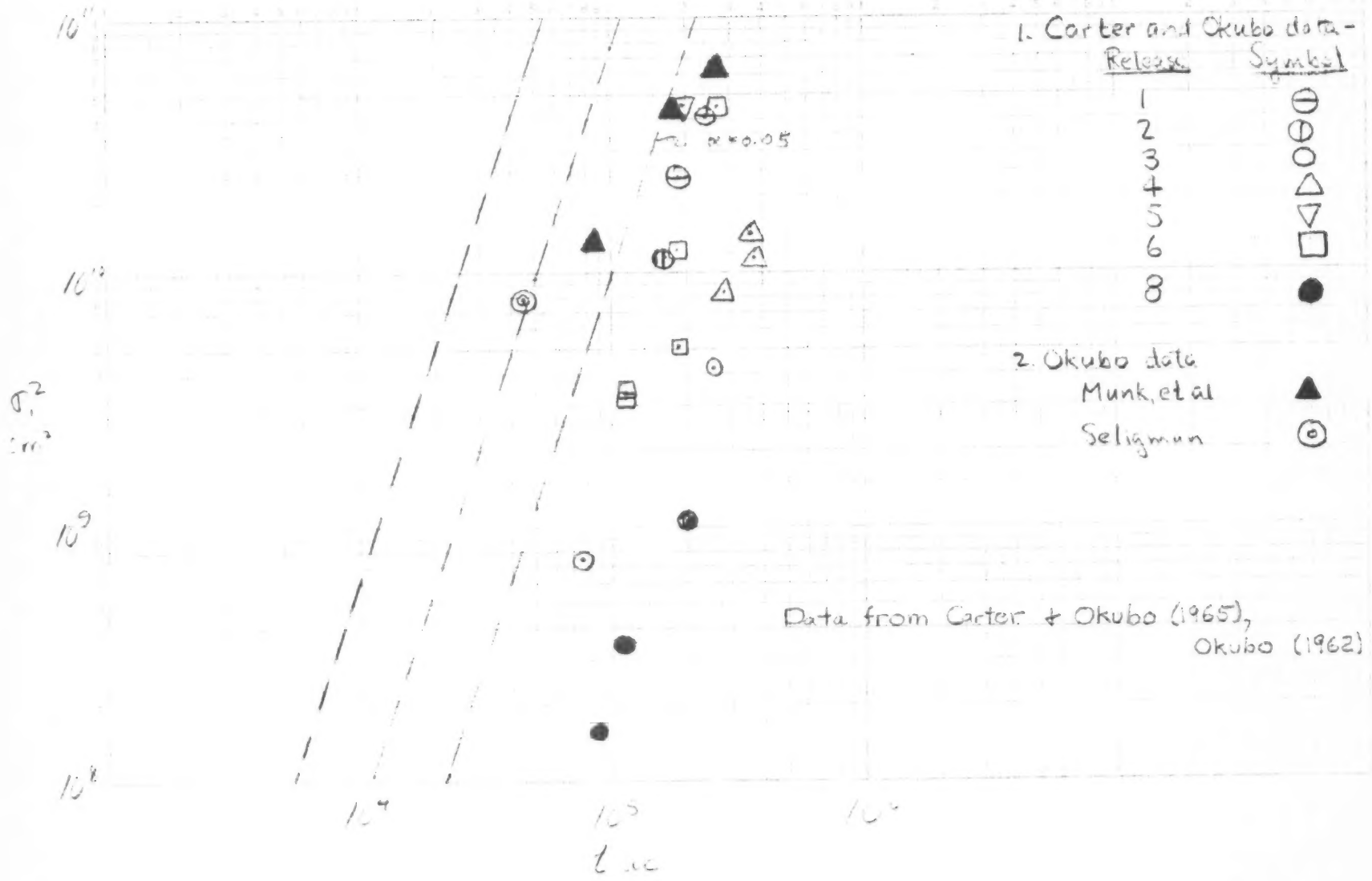

1. Carter and Okubo data -
Release
Symbol
1
2
3
4
5
6
8
2. Okubo data
Munk, et al
Seligmun
Data from Carter & Okubo (1965),
Okubo (1962)

Fig. 8

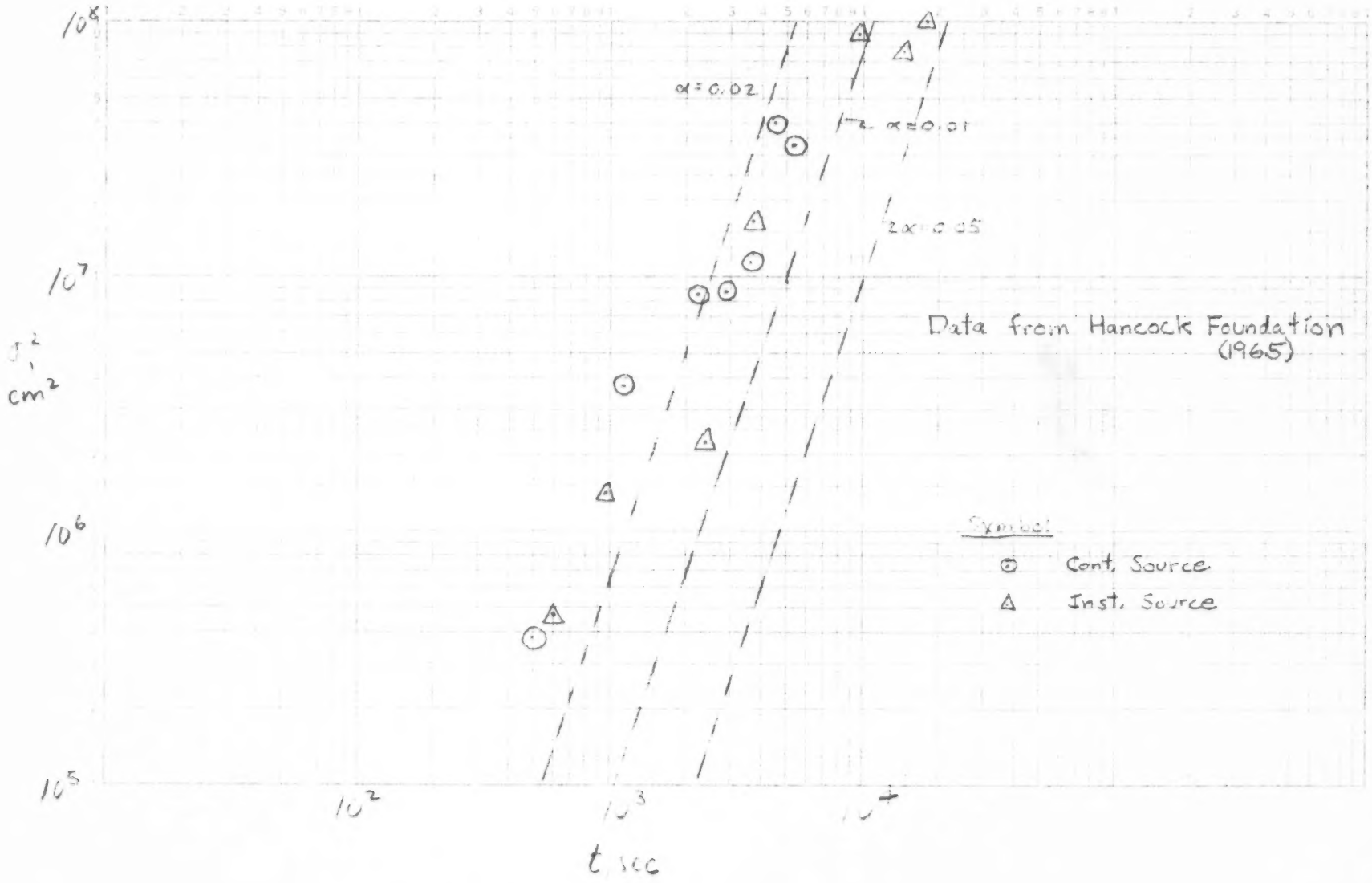

10^8
10^7
10^6
10^5
10^2
10^3
10^4
$\alpha = 0.02$
$\alpha = 0.01$
$\alpha = 0.05$
f^2, cm^2
t, sec
Data from Hancock Foundation (1965)
Symbol:
Cont. Source
Inst. Source

Fig. 9

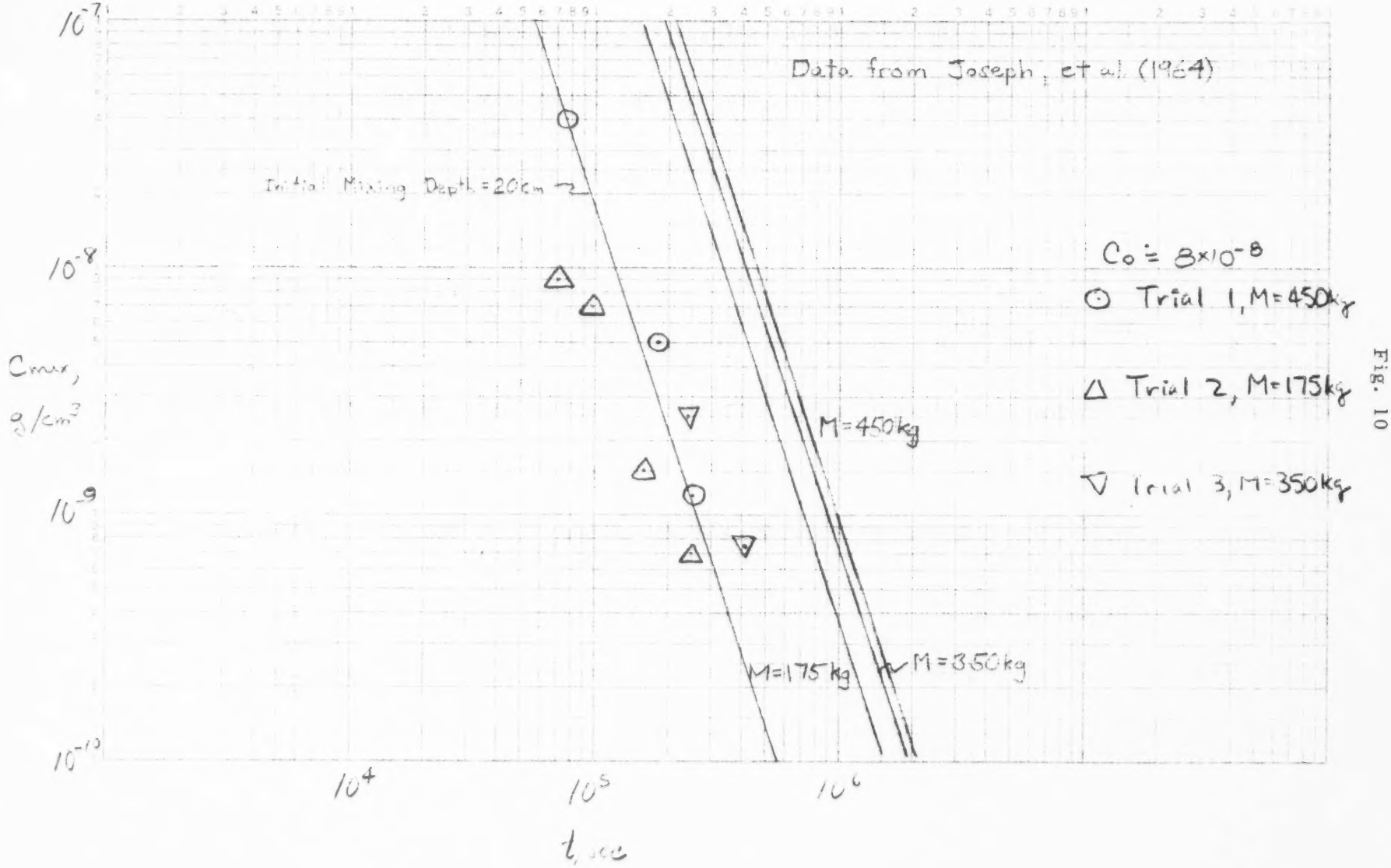
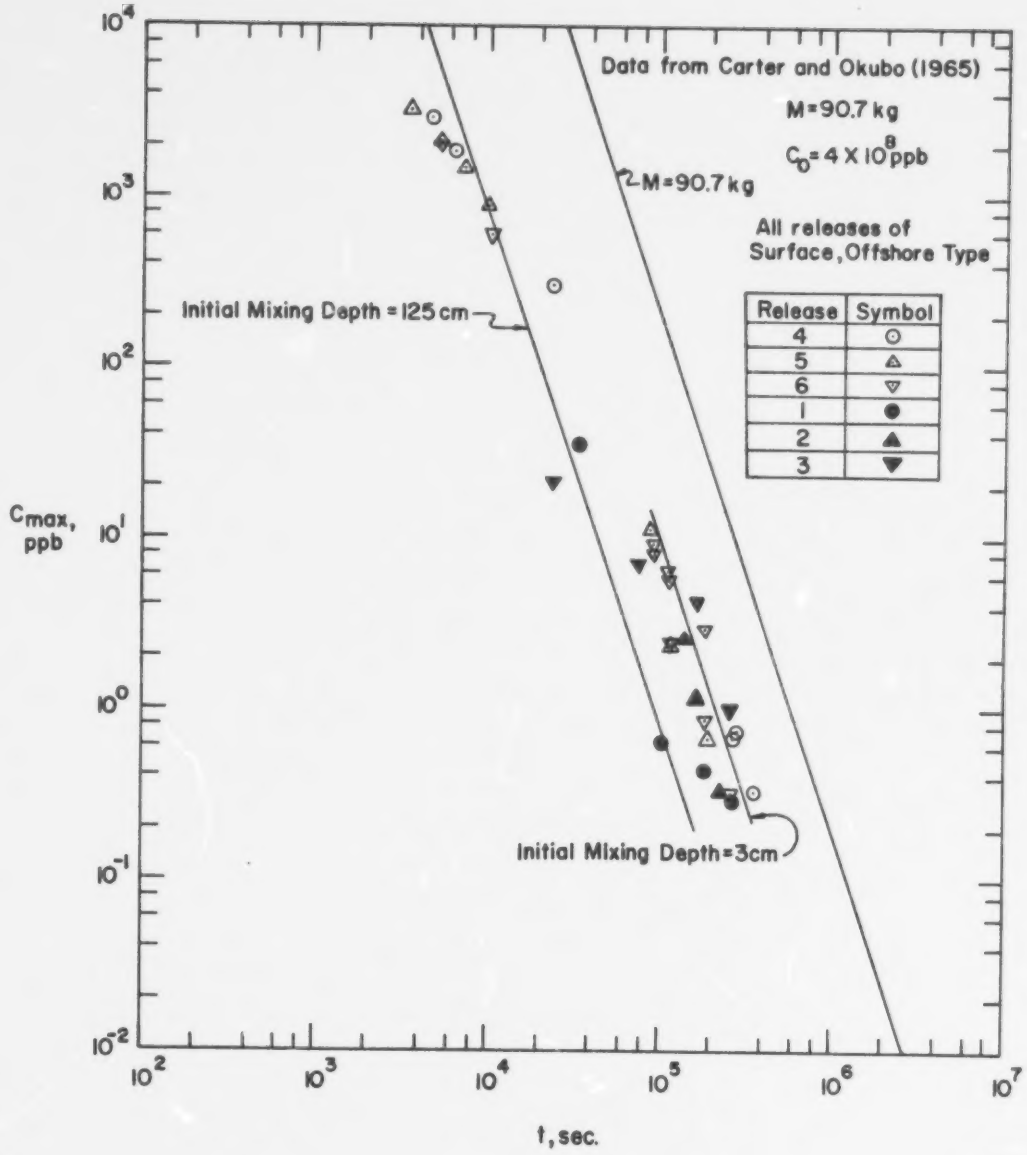

Data from Joseph, et al (1964)
Initial Mixing Depth = 20km
$C_o \doteq 8 \times 10^{-8}$
Trial 1, M = 450kg
Trial 2, M = 175kg
Trial 3, M = 350kg
M = 450kg
M = 175kg
M = 350kg
10^{-7}
10^{-8}
10^{-9}
10^{-10}
C_{max}, g/cm²
10^4
10^5
10^6
t, sec

Fig. 10

Fig. 11


Data from Carter and Okubo (1965)
M=90.7 kg
$C_0 = 4 \times 10^8$ ppb
M=90.7 kg
All releases of
Surface, Offshore Type
Release | Symbol
4
5
6
1
2
3
Initial Mixing Depth = 125 cm
Initial Mixing Depth = 3cm
C_{max}, ppb
t, sec.
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^2
10^3
10^4
10^5
10^6
10^7

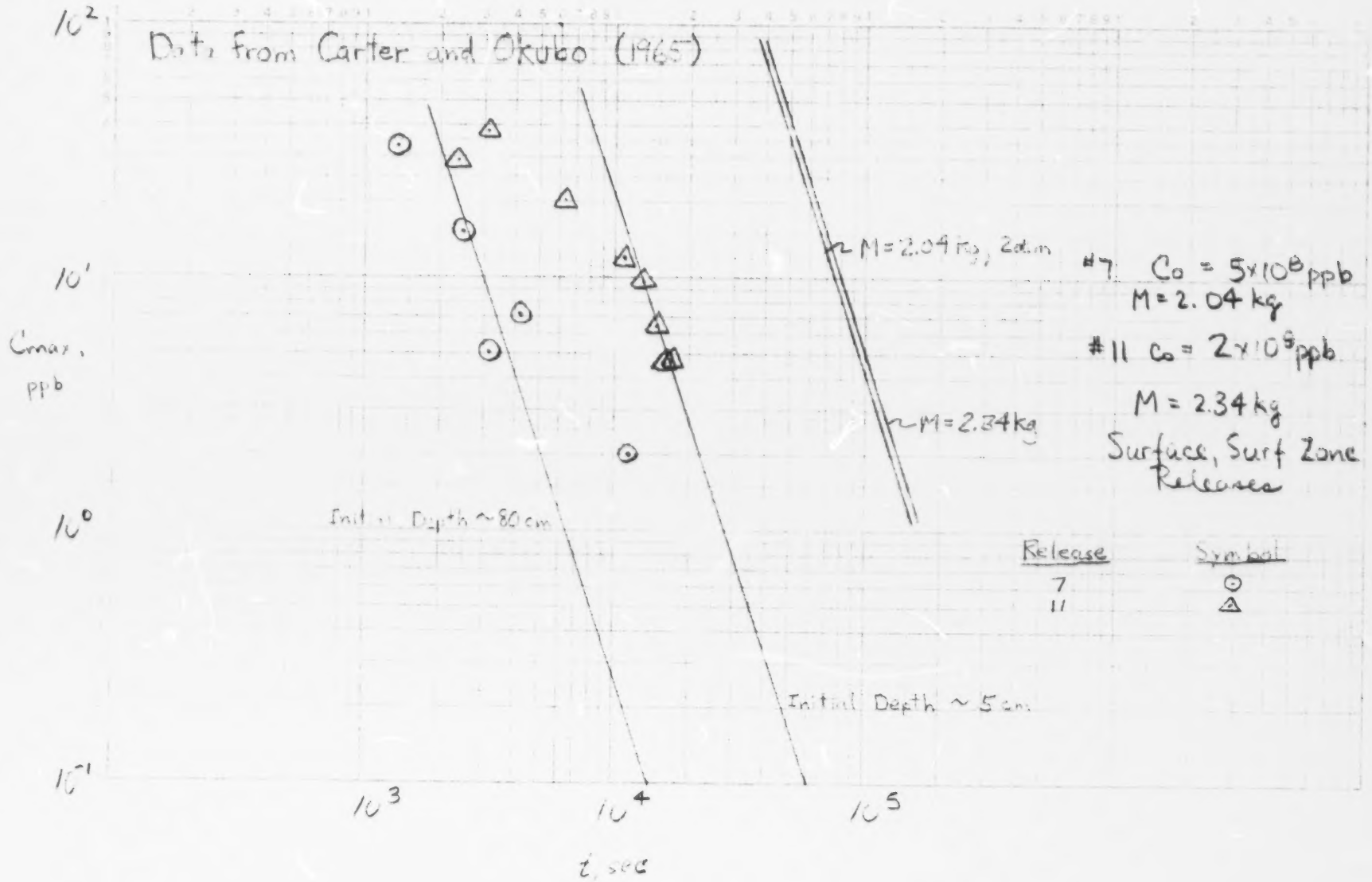

Data from Carter and Okubo (1965)
10^2
10^1
10^0
10^{-1}
Cmax, ppb
10^3
10^4
10^5
t, sec
Initial Depth ~80 cm
Initial Depth ~5 cm
~M=2.04 kg, 2d.m
~M=2.34kg
#7 $C_o = 5 \times 10^8$ ppb
M = 2.04 kg
#11 $C_o = 2 \times 10^8$ ppb
M = 2.34 kg
Surface, Surf Zone Releases
Release
Symbol
7
11

Fig. 12

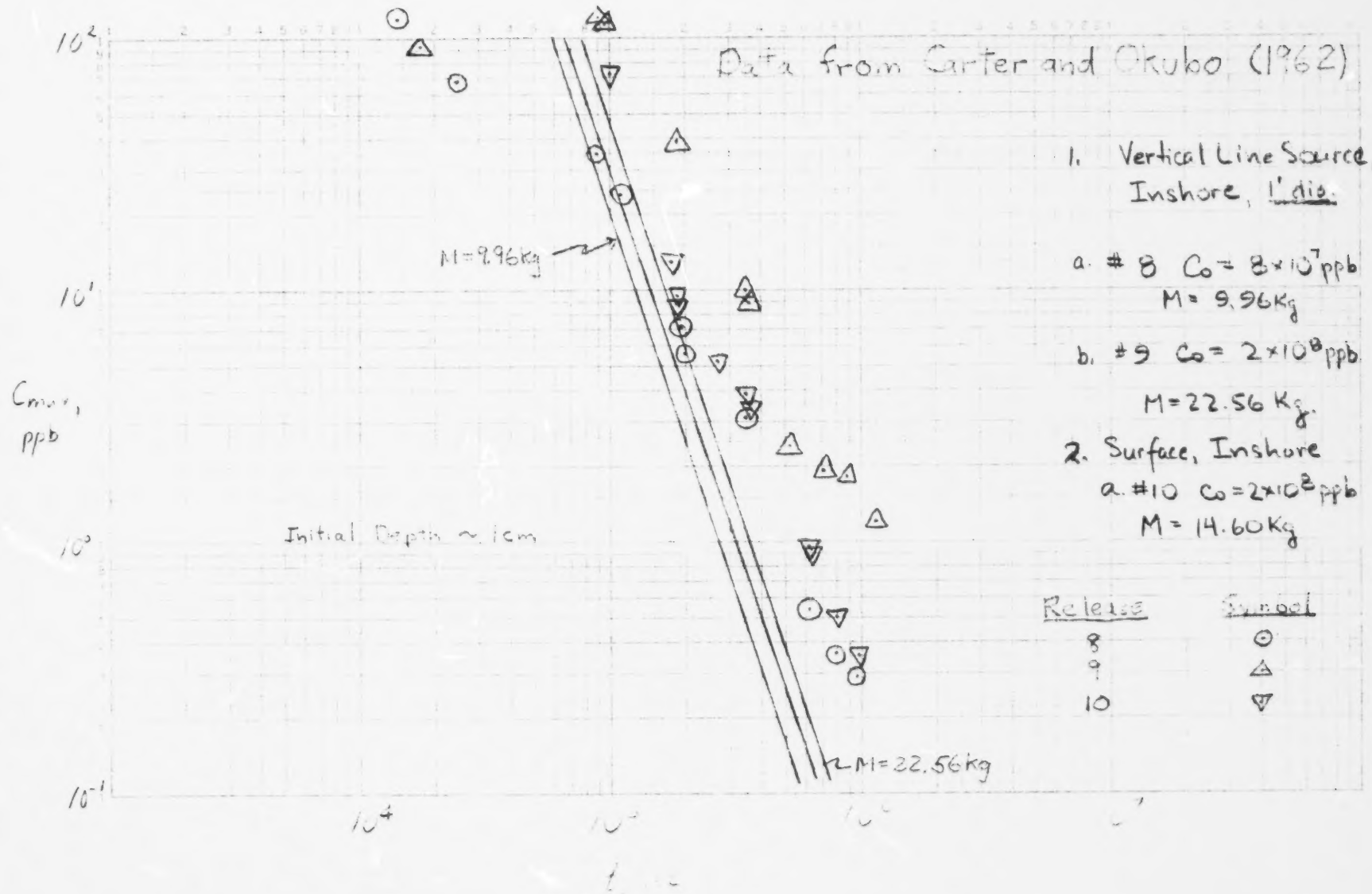
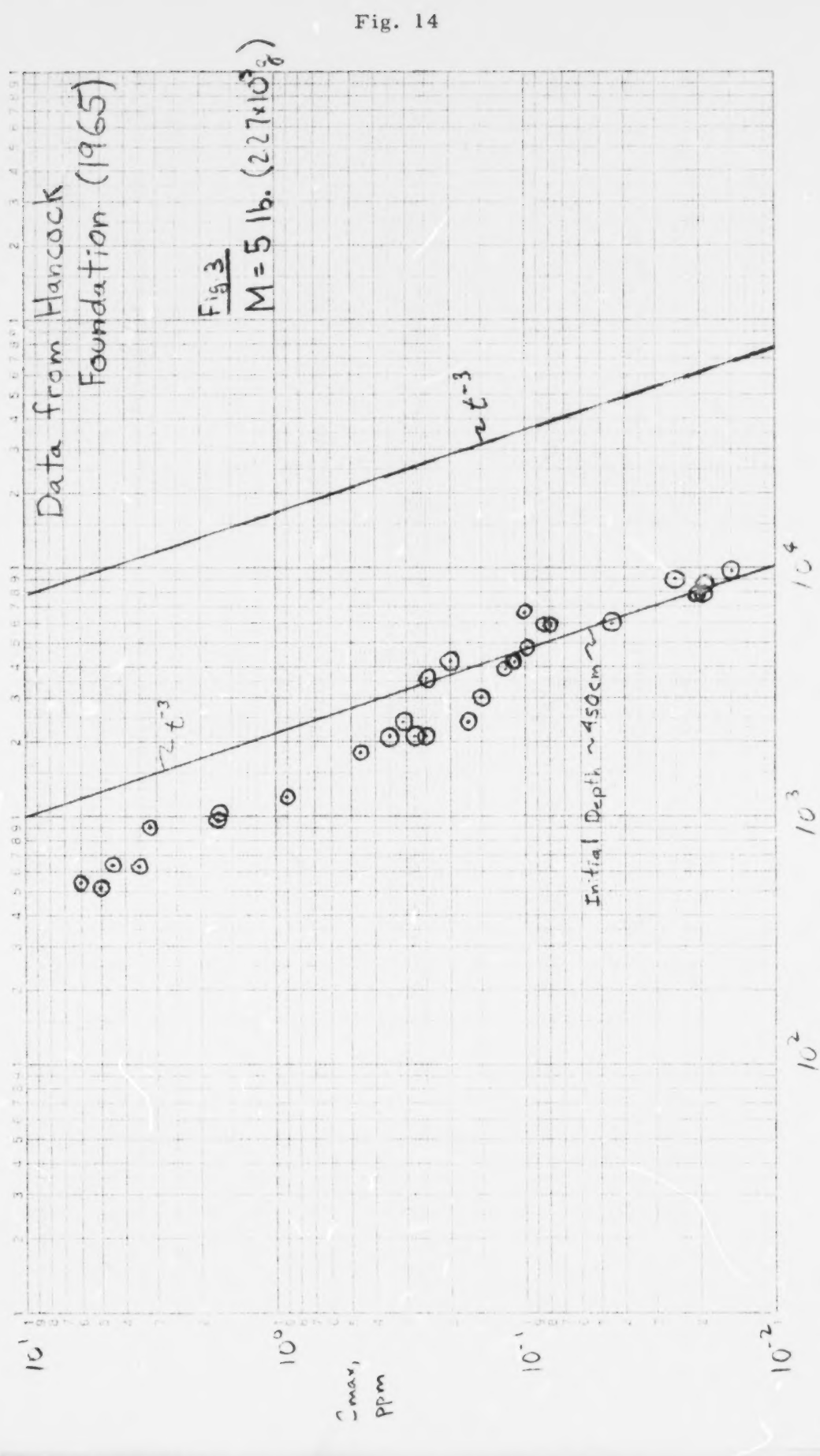

Data from Carter and Okubo (1962)
1. Vertical Line Source, Inshore, 1' dia.
a. # 8 $C_o = 8 \times 10^7$ ppb
M = 9.96 Kg
b. #9 $C_o = 2 \times 10^8$ ppb
M = 22.56 Kg.
2. Surface, Inshore
a. #10 $C_o = 2 \times 10^8$ ppb
M = 14.60 Kg
Release
Symbol
8
9
10
M = 9.96 kg
2 M = 22.56 kg
Initial Depth ~ 1 cm
C_{max}, ppb
10^2
10^1
10^0
10^{-1}
10^{-4}

Fig. 13

Fig. 14


Data from Hancock Foundation (1965)
Fig 3
M = 5 lb. (2.27×10³ g)
~t⁻³
~t⁻³
Initial Depth ~ 450 cm
10¹
10⁰
10⁻¹
10⁻²
10²
10³
10⁴
cmax, ppm
t, sec

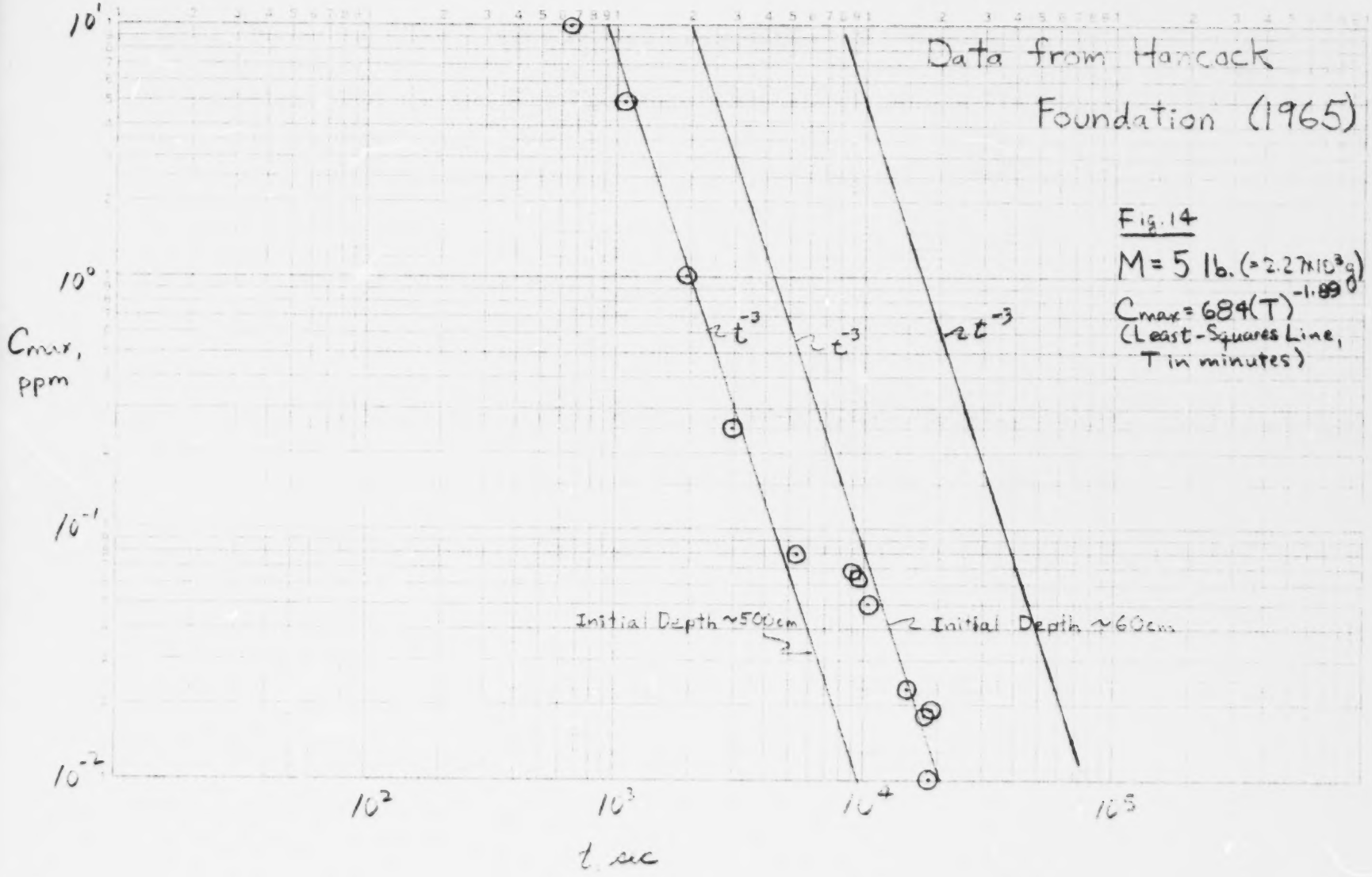

Data from Hancock Foundation (1965)
Fig. 14
M = 5 lb. (= 2.27 x 10^3 g)
Cmax = 684(T)^-1.89
(Least-Squares Line, T in minutes)
~ t^-3
~ t^-3
~ t^-3
Initial Depth ~ 50 cm
Initial Depth ~ 60 cm
Cmax, ppm
t, sec
10^1
10^0
10^-1
10^-2
10^2
10^3
10^4
10^5

Fig. 15

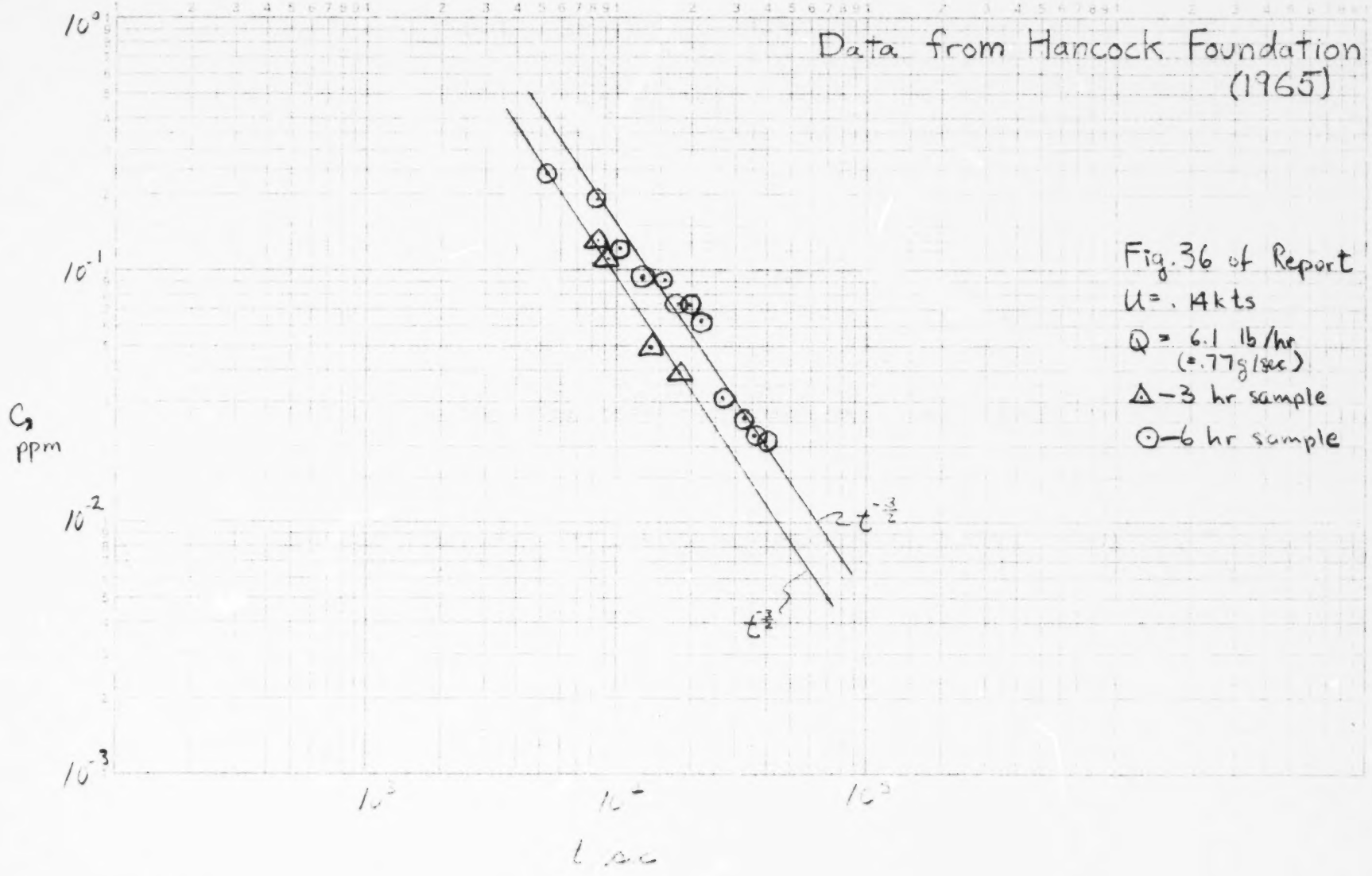

Data from Hancock Foundation (1965)
Fig. 36 of Report
U = .14 kts
Q = 6.1 lb/hr (.77 g/sec)
△ – 3 hr sample
⊙ – 6 hr sample
$t^{-\frac{3}{2}}$
$t^{-\frac{3}{2}}$
C_g ppm
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
t sec

Fig. 16

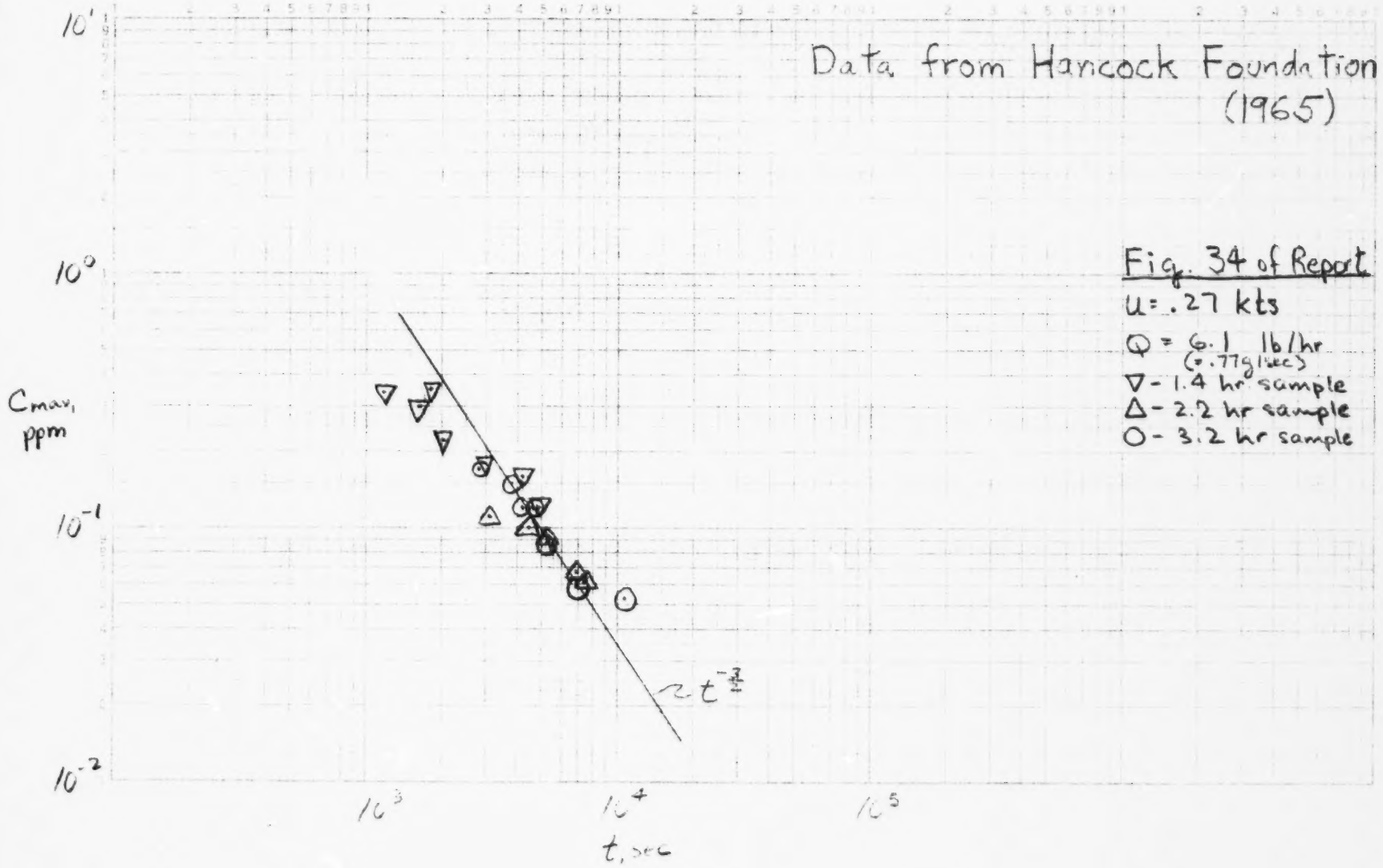

Data from Hancock Foundation (1965)
Fig. 34 of Report
u = .27 kts
Q = 6.1 lb/hr (.77 g/sec)
▽ - 1.4 hr sample
△ - 2.2 hr sample
○ - 3.2 hr sample
C_{max}, ppm
10^{1}
10^{0}
10^{-1}
10^{-2}
$\sim t^{-\frac{3}{4}}$
10^{3}
10^{4}
10^{5}
t, sec

Fig. 17

Fig. 18

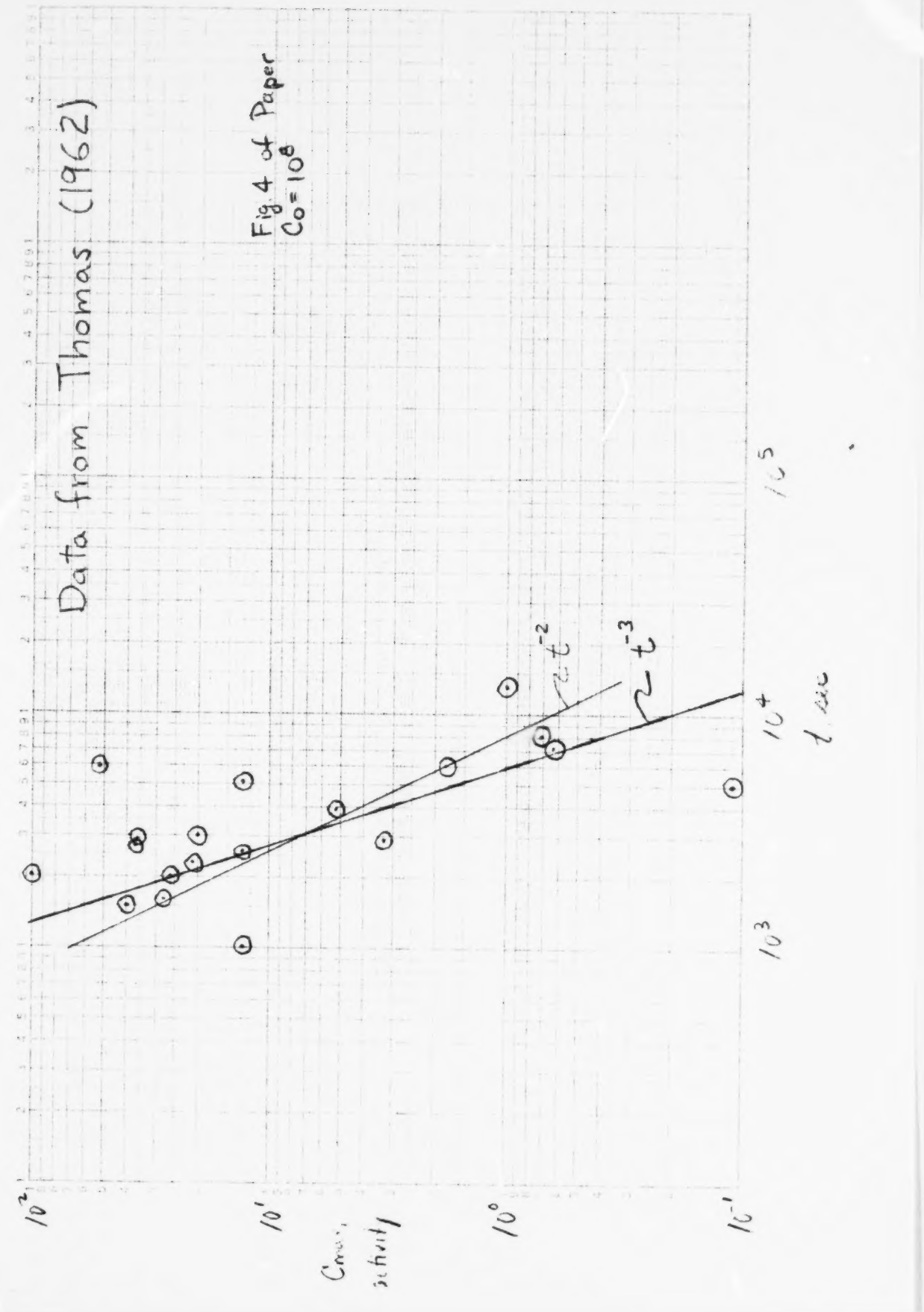
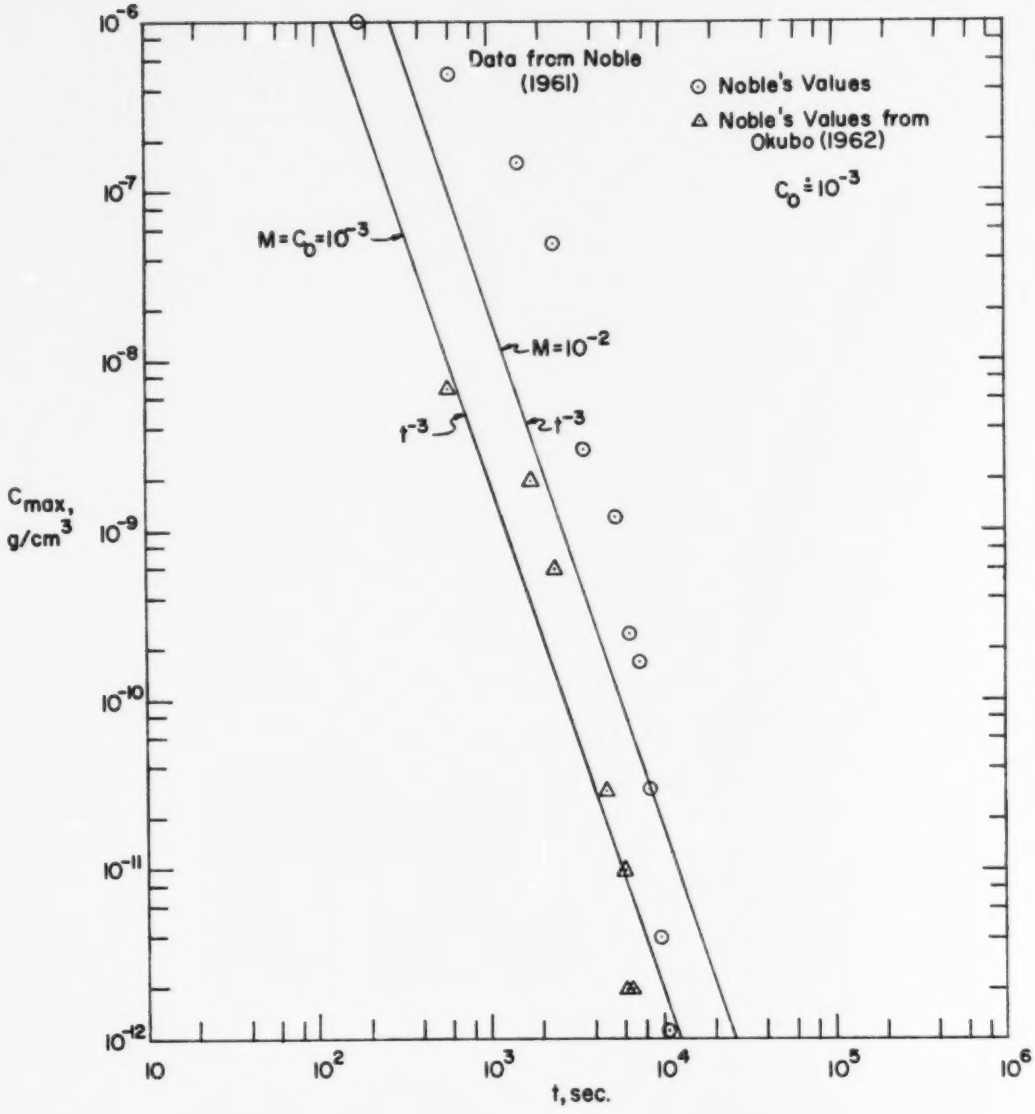

Data from Thomas (1962)
Fig. 4 of Paper
$C_0 = 10^8$
$\sim t^{-2}$
$\sim t^{-3}$
10^2
10^1
10^0
10^{-1}
10^3
10^4
10^5
t, sec

Fig. 19


Data from Noble (1961)
Noble's Values
Noble's Values from Okubo (1962)
$C_0 \doteq 10^{-3}$
$M = C_0 = 10^{-3}$
$M = 10^{-2}$
t^{-3}
$2t^{-3}$
C_{max}, g/cm^3
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10
10^2
10^3
10^4
10^5
10^6
t, sec.

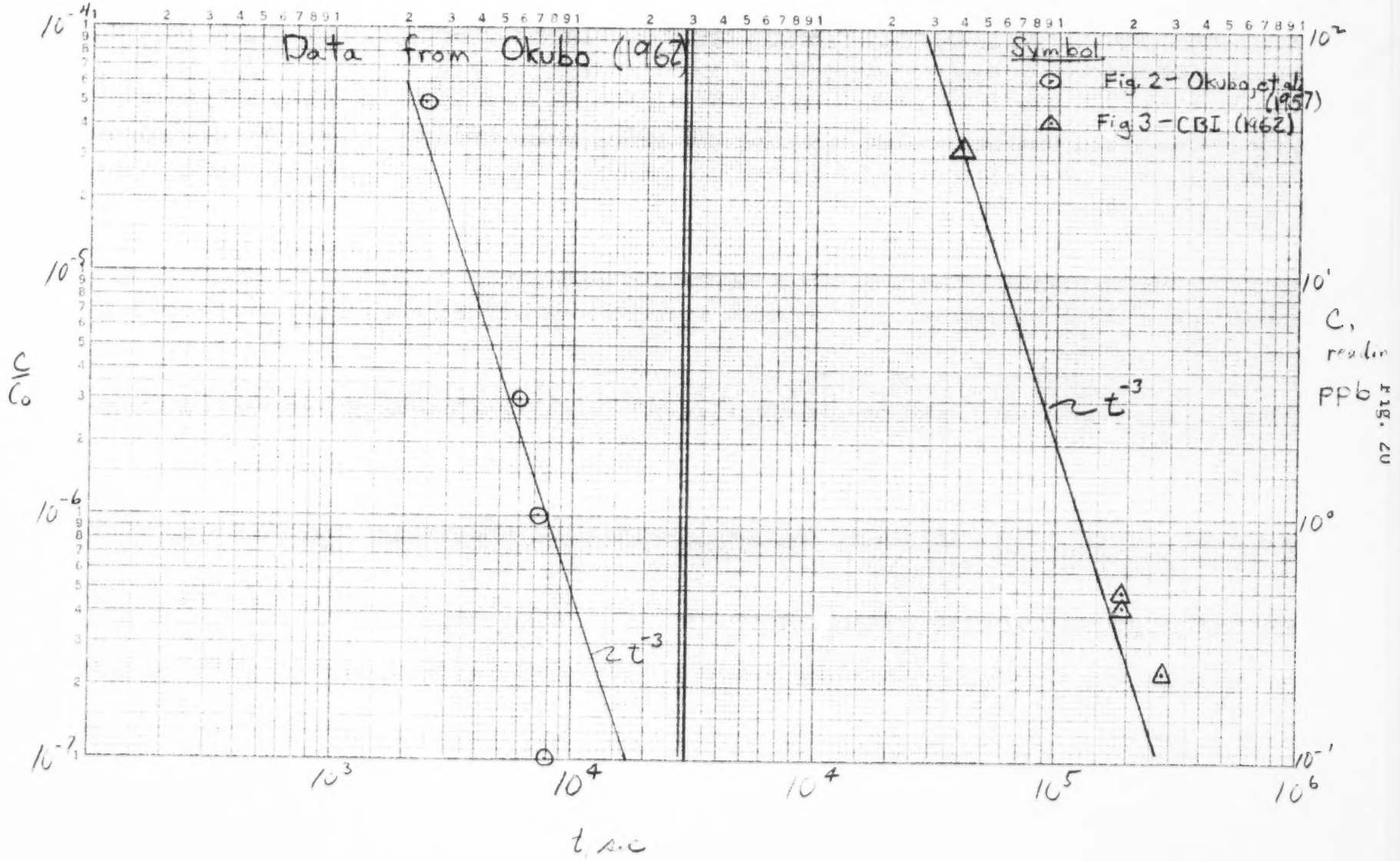

Data from Okubo (1967)
Symbol
Fig. 2 - Okubo, et al (1957)
Fig 3 - CBI (1962)
$\sim t^{-3}$
$2t^{-3}$
C/C₀
C, realin ppb
t, s.c
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{3}
10^{4}
10^{4}
10^{5}
10^{6}

Fig. 20

Fig. 21

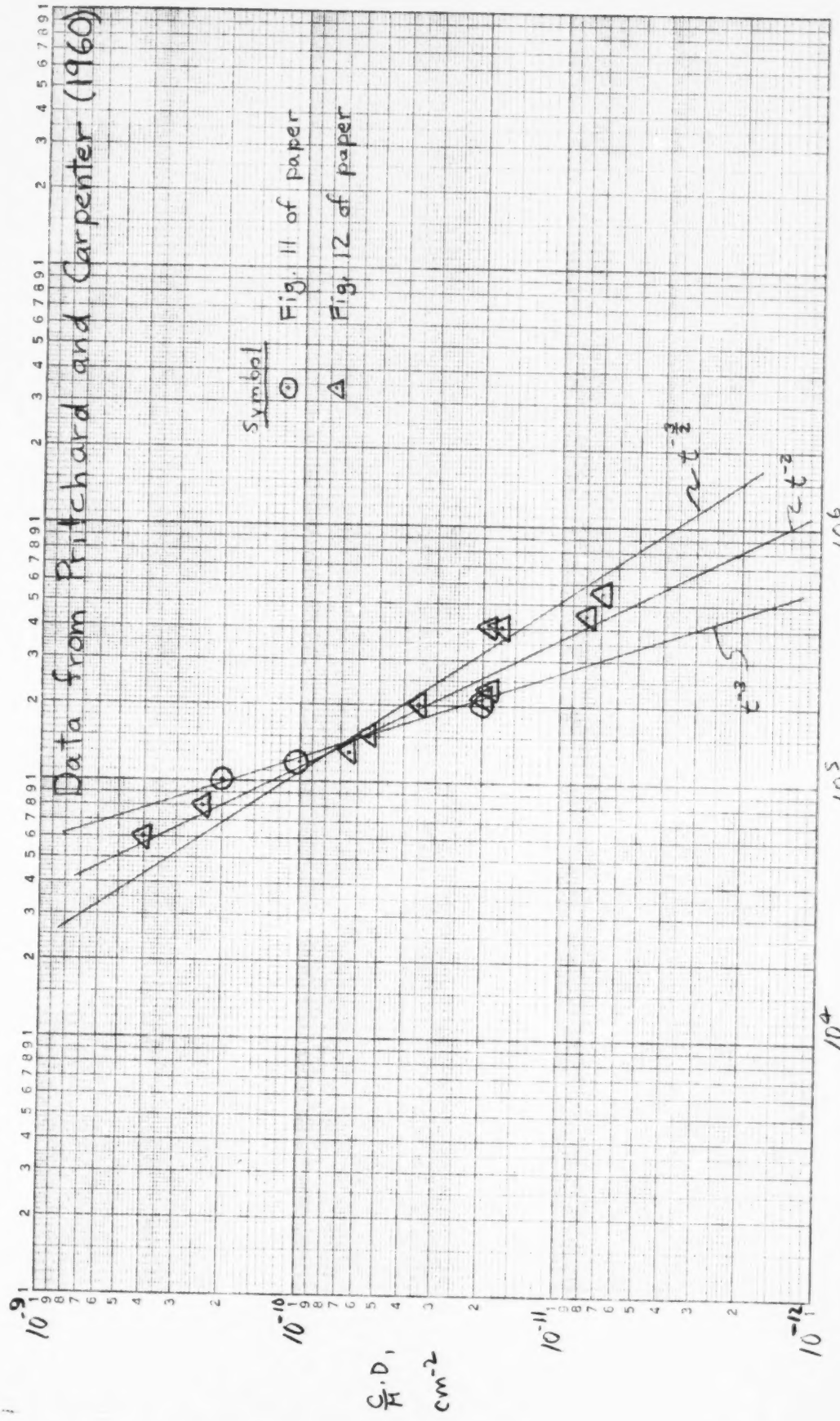
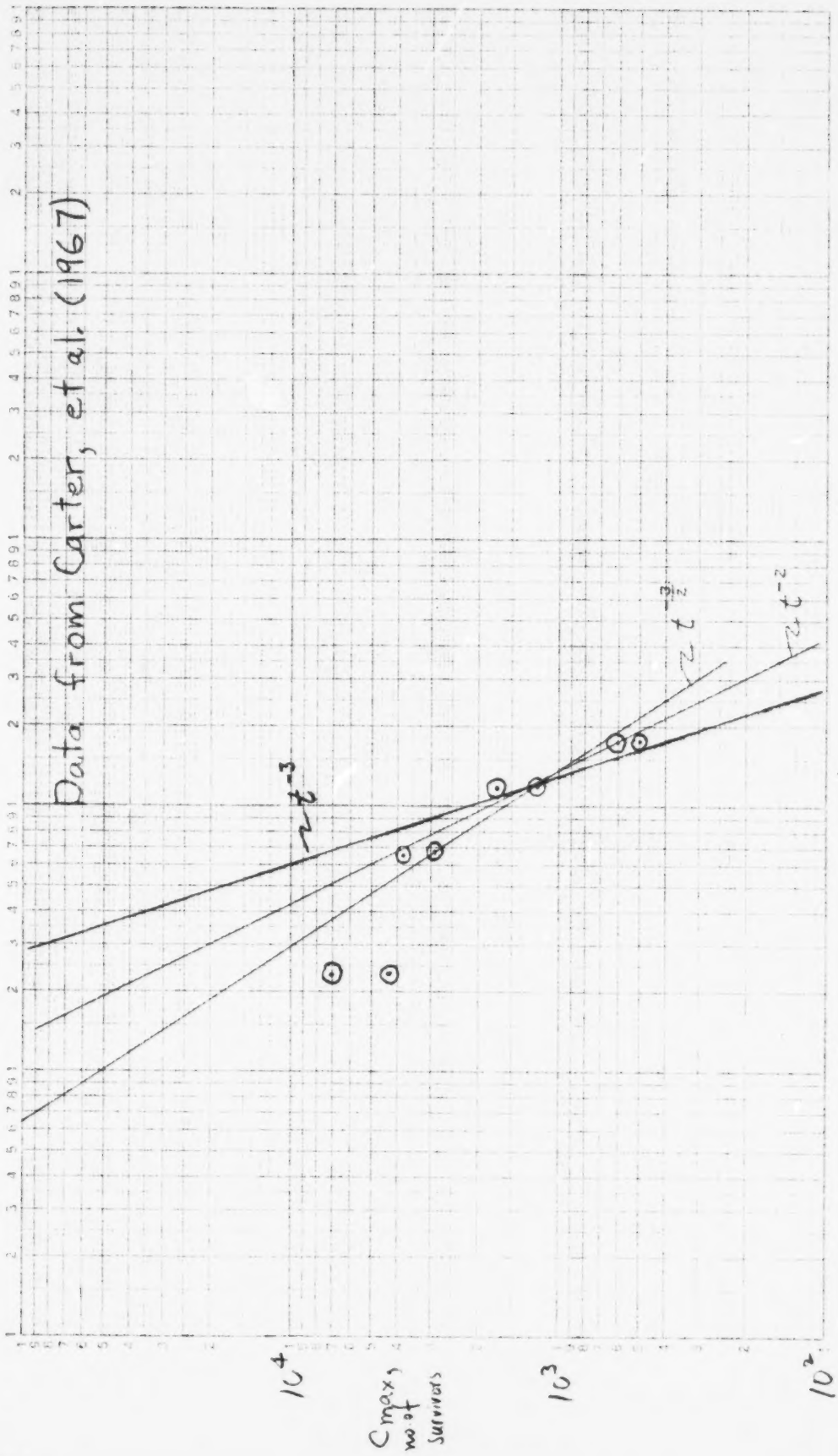

Data from Pritchard and Carpenter (1960)
Symbol
⊙ Fig. 11 of paper
△ Fig. 12 of paper
$t^{-\frac{3}{2}}$
t^{-2}
t^{-3}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^4
10^5
10^6
$\frac{C_f \cdot D}{H}$, cm^{-2}
t, sec

Fig. 22


Data from Carter, et al. (1967)
$\sim t^{-3}$
$\sim t^{-\frac{3}{2}}$
$\sim t^{-2}$
10^2
10^3
10^4
10^5
C_{max}, no of survivors
t, sec

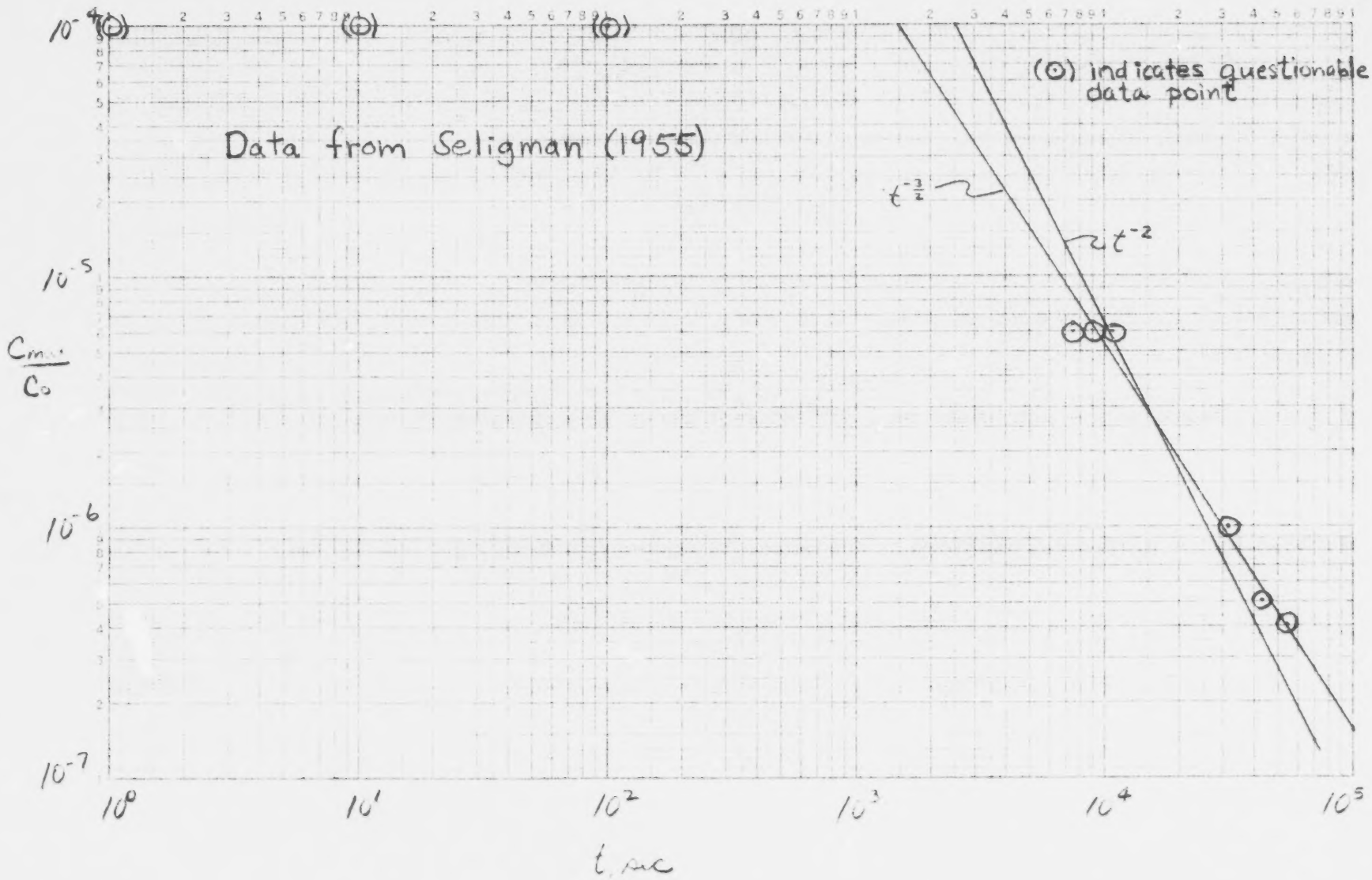
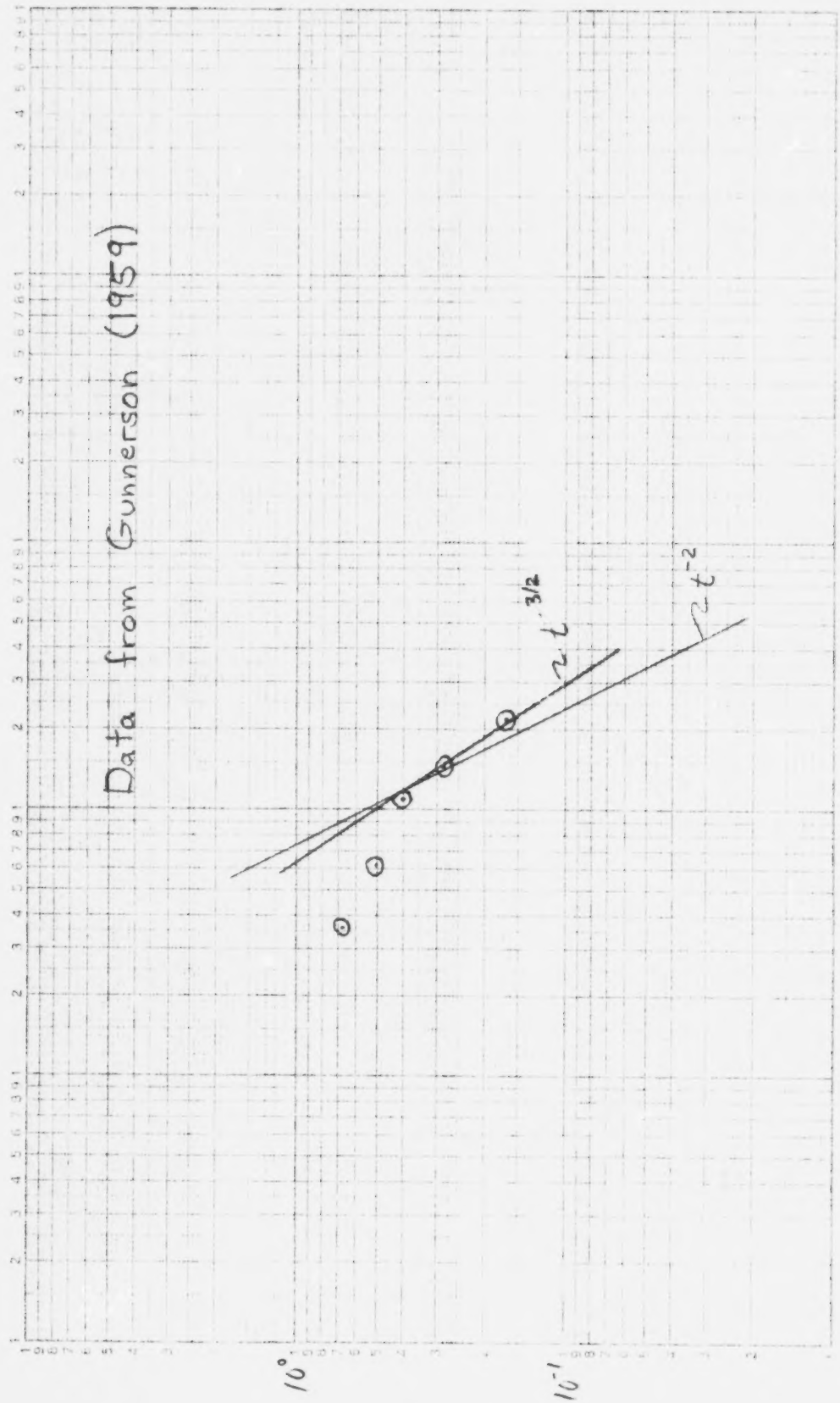

Data from Seligman (1955)
(⊙) indicates questionable data point
$t^{-\frac{3}{2}}$
t^{-2}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\frac{C_{max.}}{C_o}$
10^0
10^1
10^2
10^3
10^4
10^5
t, sec

Fig. 23

Fig. 24


Data from Gunnerson (1959)
$\propto t^{3/2}$
$\propto t^{-2}$
10^0
10^1
10^3
10^4
10^5
t, sec

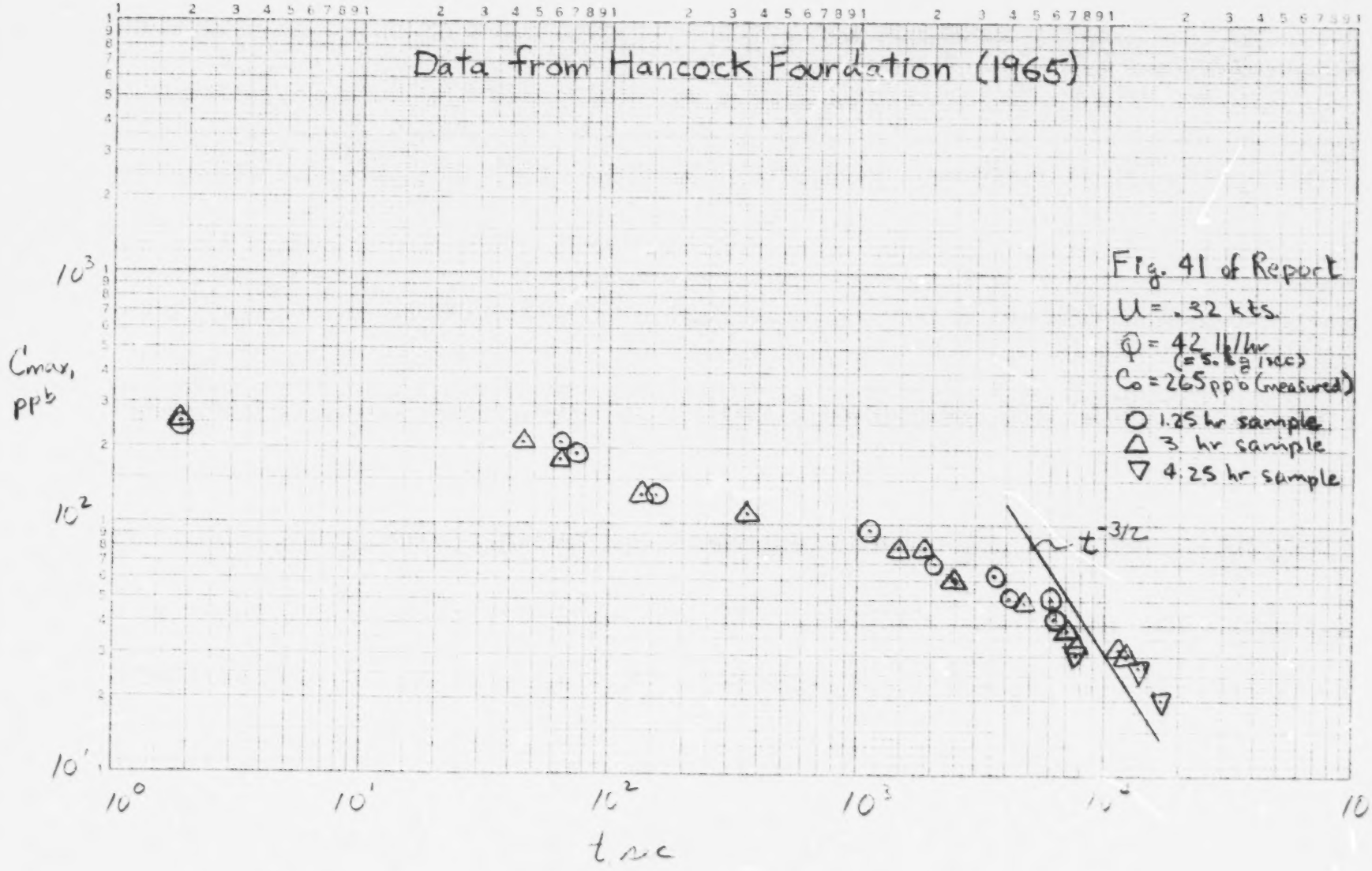

Data from Hancock Foundation (1965)
Fig. 41 of Report
U = .32 kts
Q = 42 lb/hr (= 5.3 g/sec)
Co = 265 ppb (measured)
1.25 hr sample
3 hr sample
4.25 hr sample
~ t^-3/2
Cmax, ppb
t sec
10^0
10^1
10^2
10^3
10^4
10^5
10^3
10^2
10^1

Fig. 25

Fig. 26

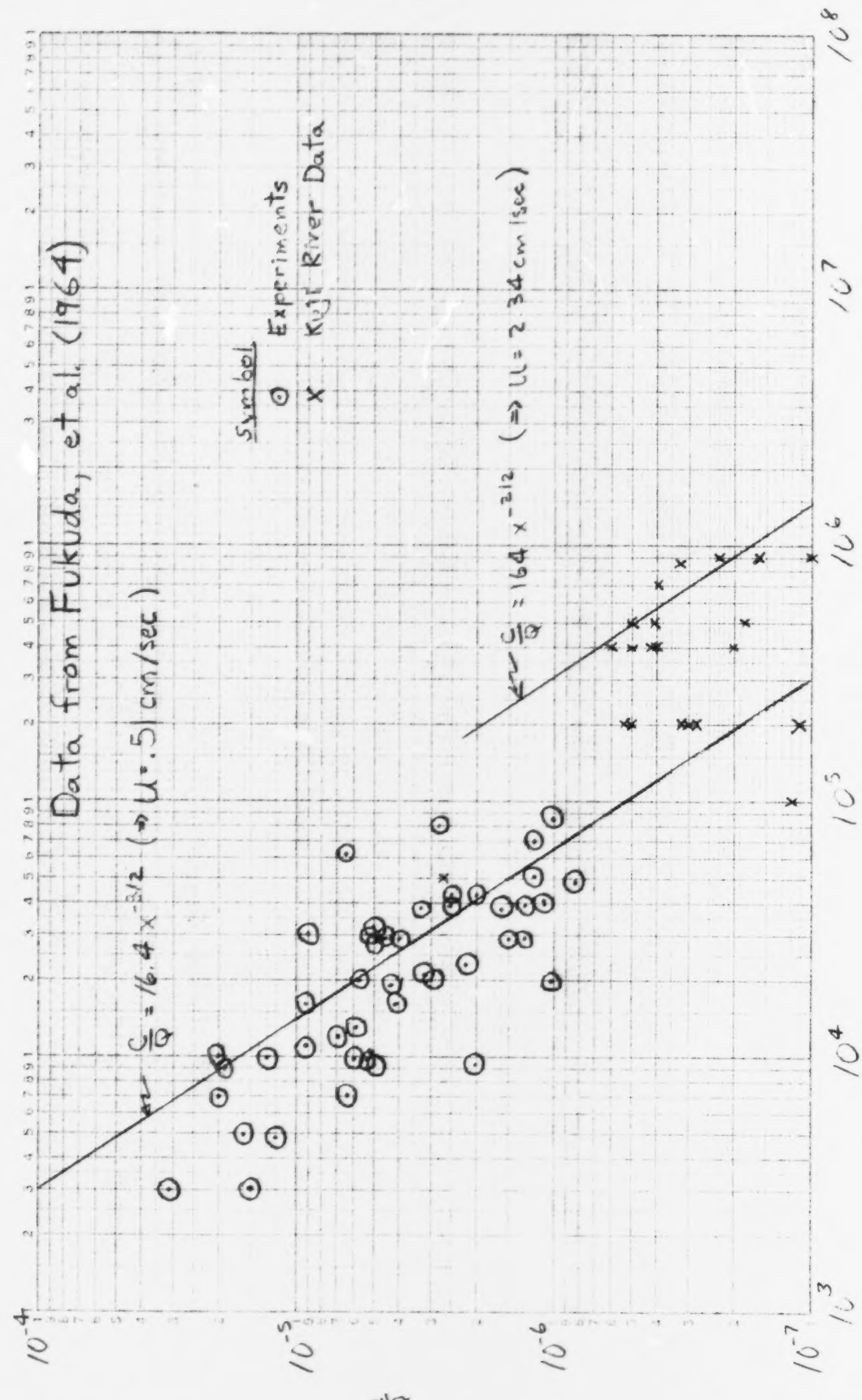
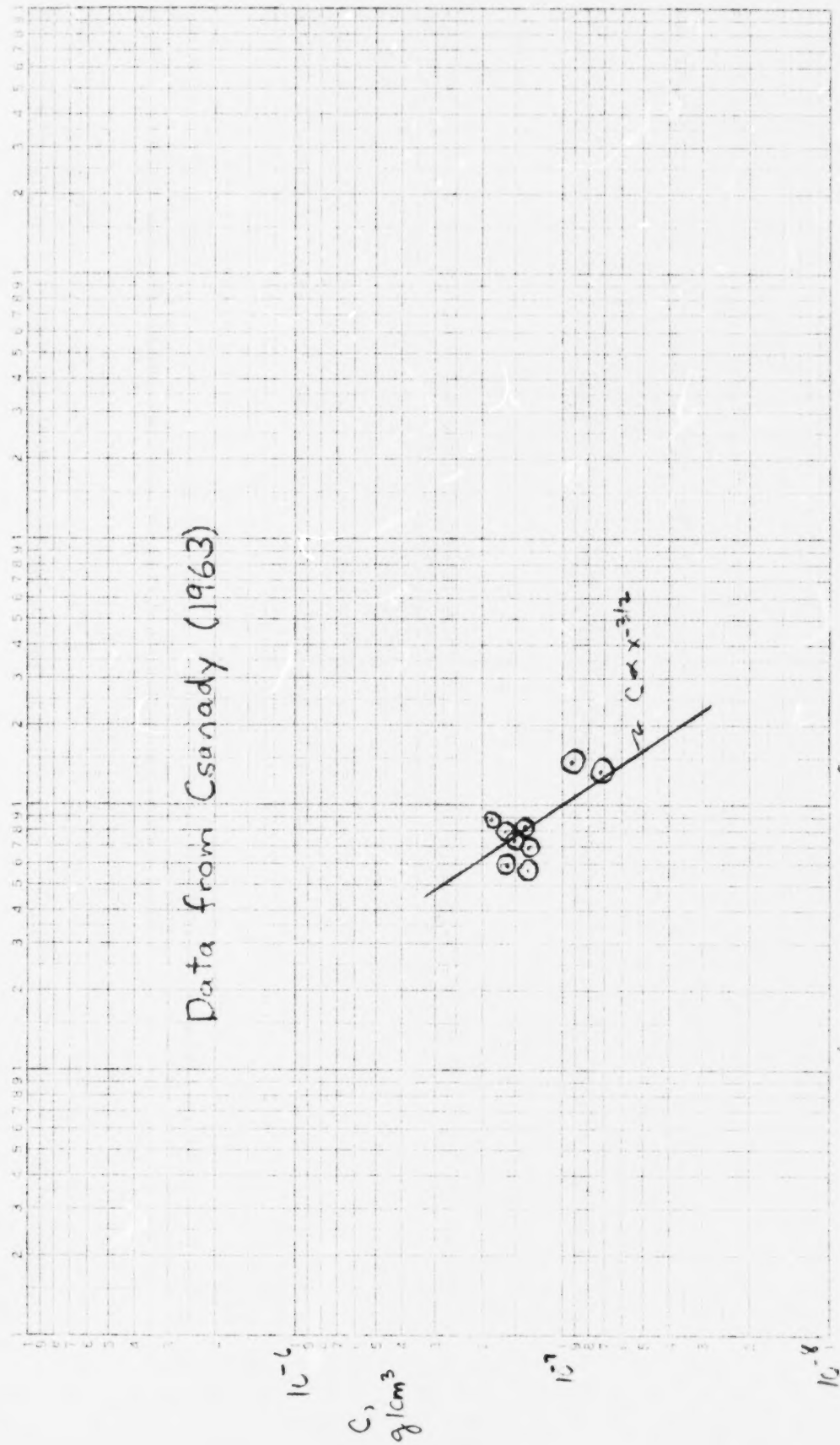

Data from Fukuda, et al. (1964)
Symbol
Experiments
Kuji River Data
$\frac{C}{\Theta} = 16.4\, x^{-3/2}$ ($\Rightarrow U_* = .5$ cm/sec)
$\frac{C}{\Theta} = 164\, x^{-3/2}$ ($\Rightarrow U_* = 2.34$ cm/sec)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
x, cm
C/Θ

Fig. 27



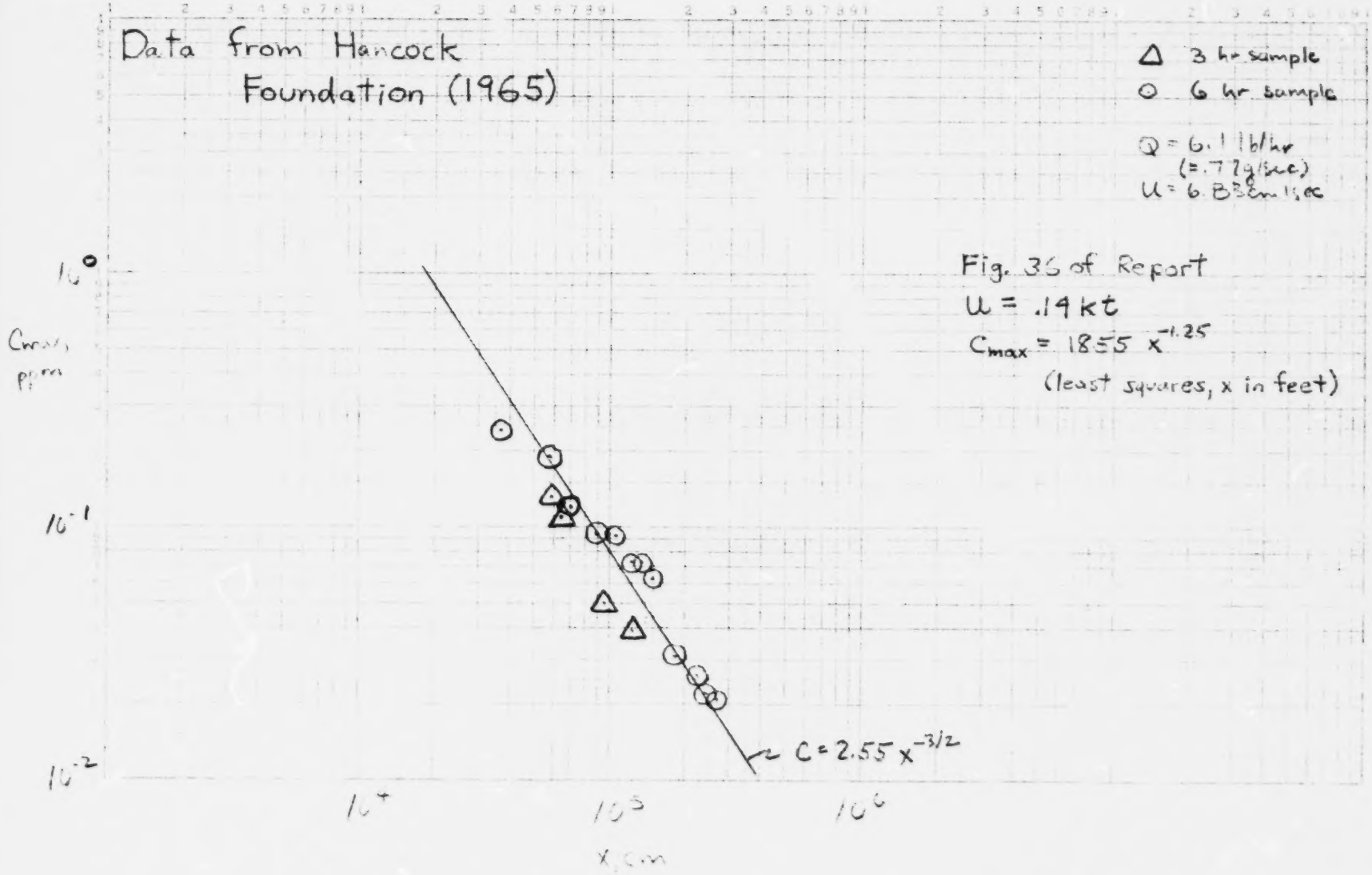

Data from Hancock Foundation (1965)
△ 3 hr sample
○ 6 hr sample
Q = 6.1 lb/hr (= .77 g/sec)
u = 6.8 km/hr
Fig. 36 of Report
u = .14 kt
$C_{max} = 1855\ x^{-1.25}$
(least squares, x in feet)
$C = 2.55\ x^{-3/2}$
10^0
10^{-1}
10^{-2}
10^4
10^5
10^6
x, cm

Fig. 28

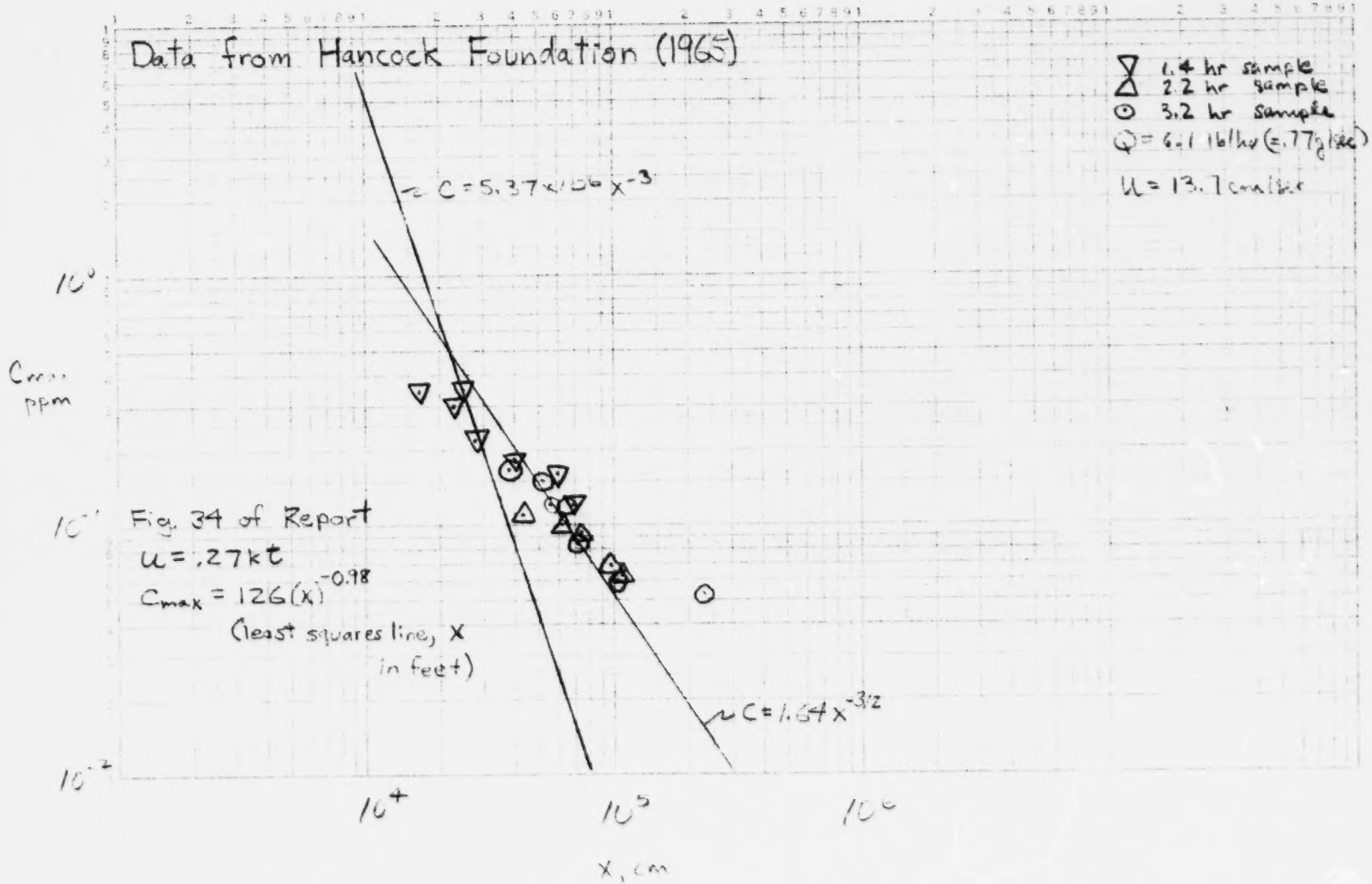

Data from Hancock Foundation (1965)
1.4 hr sample
2.2 hr sample
3.2 hr sample
Q = 6.1 lb/hr (.77 g/sec)
u = 13.7 cm/sec
C = 5.37 x 10^6 x^-3
C = 1.64 x^-3/2
Fig. 34 of Report
u = .27 kt
Cmax = 126(x)^-0.98
(least squares line, x in feet)
Cmax ppm
10^0
10^-1
10^-2
10^4
10^3
10^2
x, cm

Fig. 29

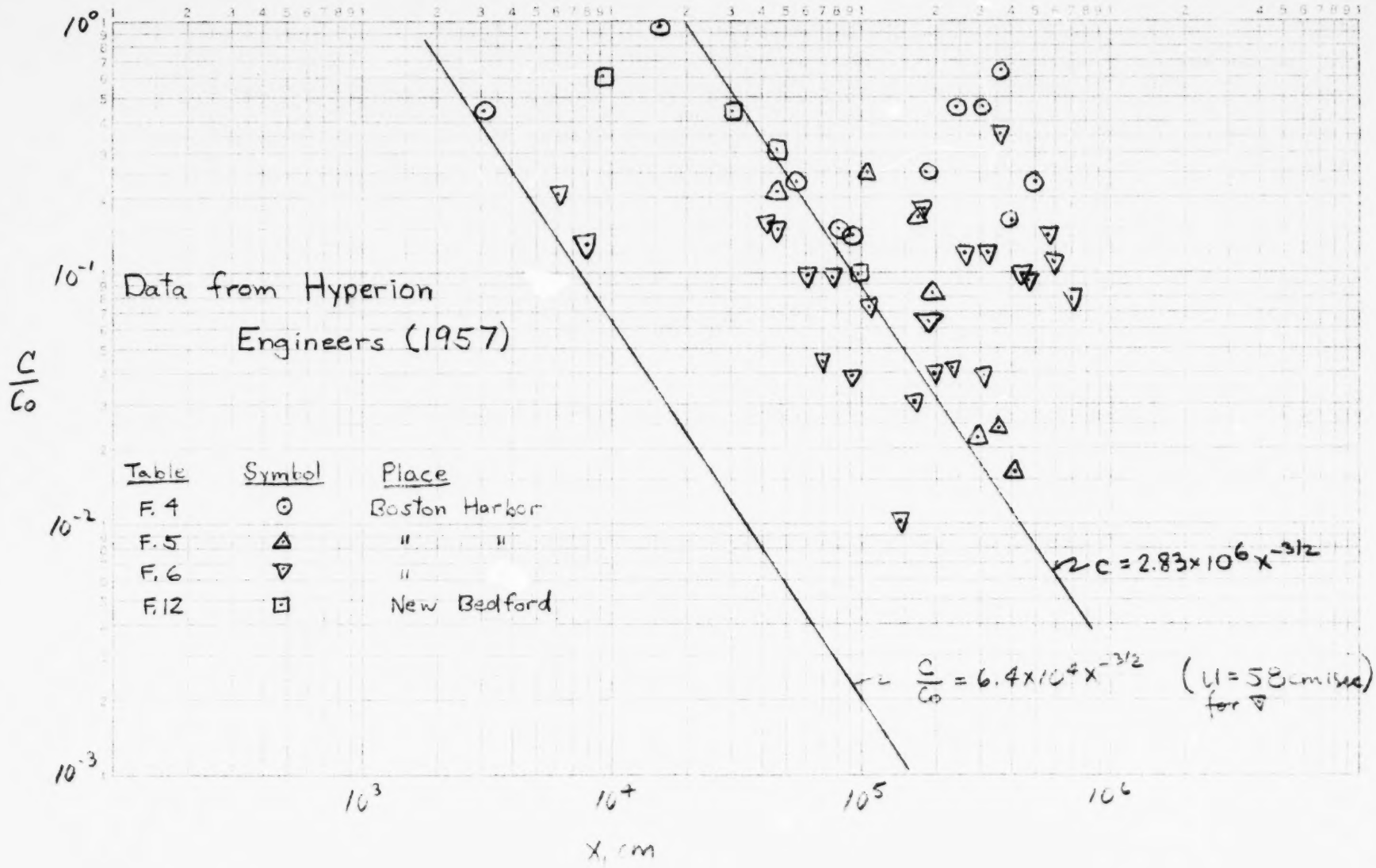

Data from Hyperion Engineers (1957)
Table Symbol Place
F. 4 Boston Harbor
F. 5 " "
F. 6 "
F. 12 New Bedford
$\frac{C}{C_0} = 2.83 \times 10^6 x^{-3/2}$
$\frac{C}{C_0} = 6.4 \times 10^4 x^{-3/2}$ ($U = 58$ cm/sec for ▽)
$\frac{C}{C_0}$
X, cm
10^0
10^{-1}
10^{-2}
10^{-3}
10^3
10^4
10^5
10^6

Fig. 30

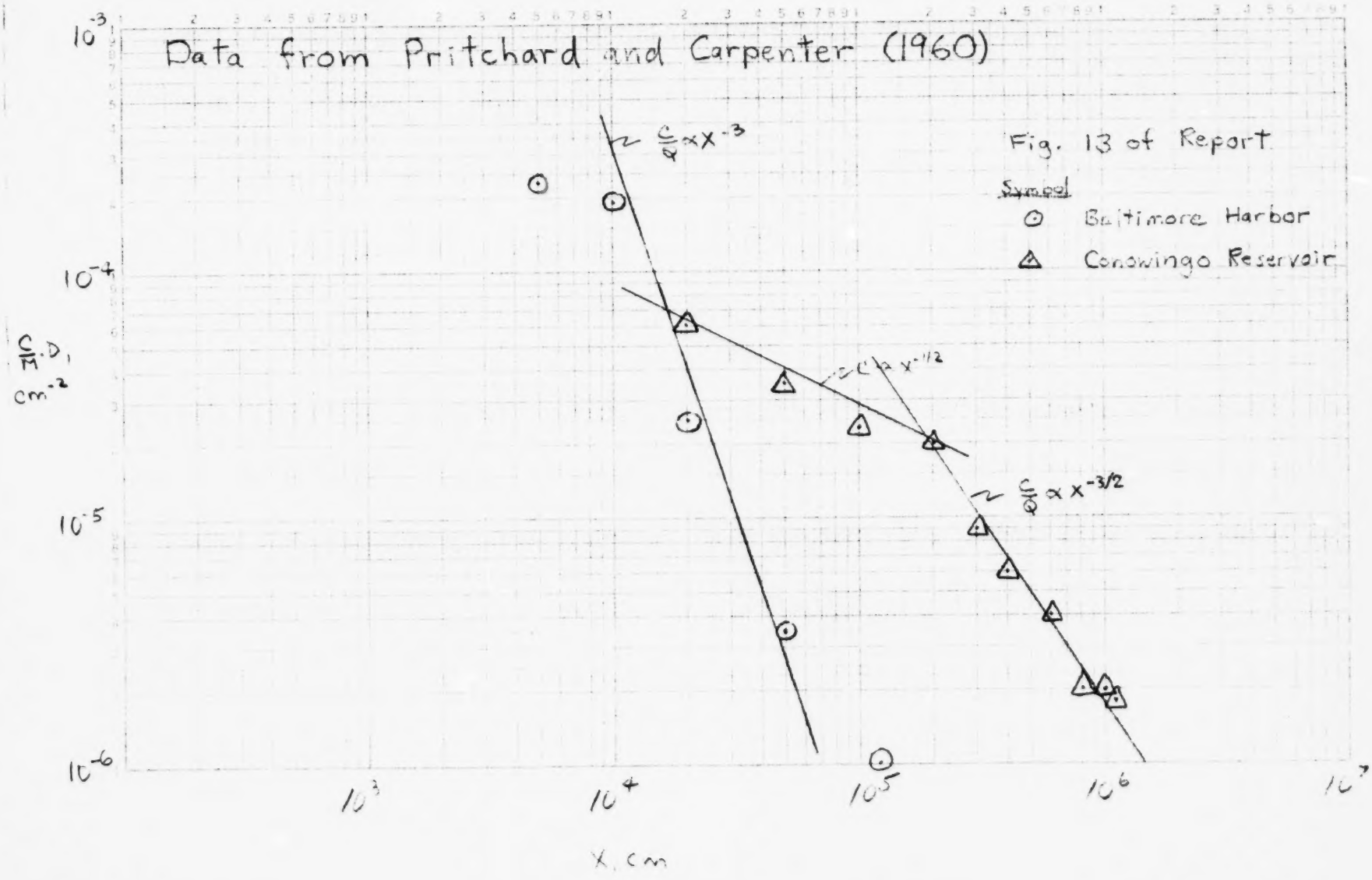
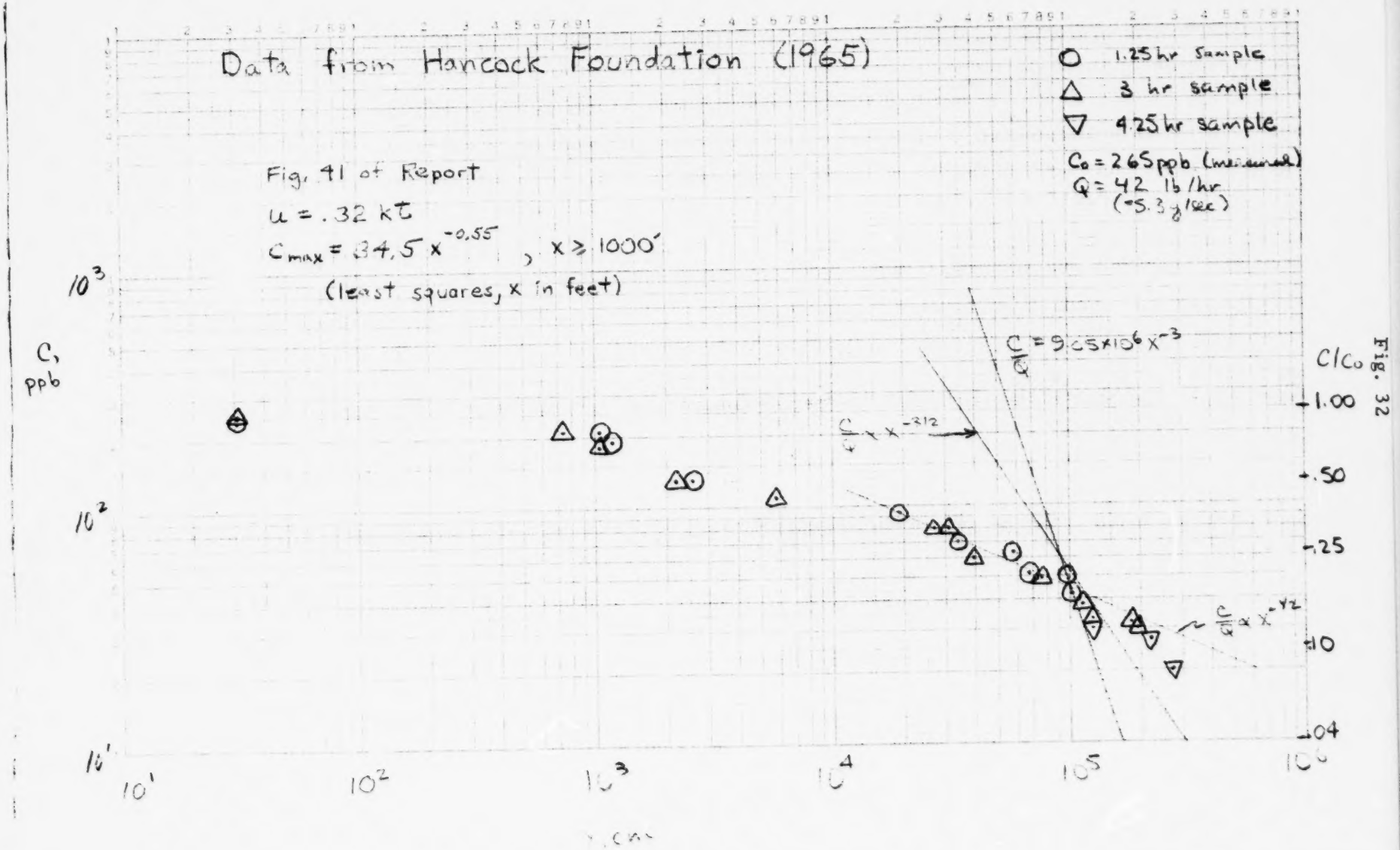

Data from Pritchard and Carpenter (1960)
Fig. 13 of Report
Symbol
Baltimore Harbor
Conowingo Reservoir
$\frac{C}{Q} \propto X^{-3}$
$\frac{C}{Q} \propto X^{-1/2}$
$\frac{C}{Q} \propto X^{-3/2}$
$\frac{C}{Q} \cdot D$, cm^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
X, cm

Fig. 31


Data from Hancock Foundation (1965)
1.25 hr sample
3 hr sample
4.25 hr sample
C_o = 265 ppb (measured)
Q = 42 lb/hr (=5.3 g/sec)
Fig. 41 of Report
u = .32 kt
$C_{max} = 34.5 x^{-0.55}$, x ≥ 1000'
(least squares, x in feet)
C, ppb
$C/Q = 9.65 \times 10^6 x^{-3}$
$C/Q \propto x^{-2/2}$
$C/Q \propto x^{-4/2}$
C/Co
1.00
.50
.25
.10
.04
10^3
10^2
10^1
10^4
10^5
Fig. 32

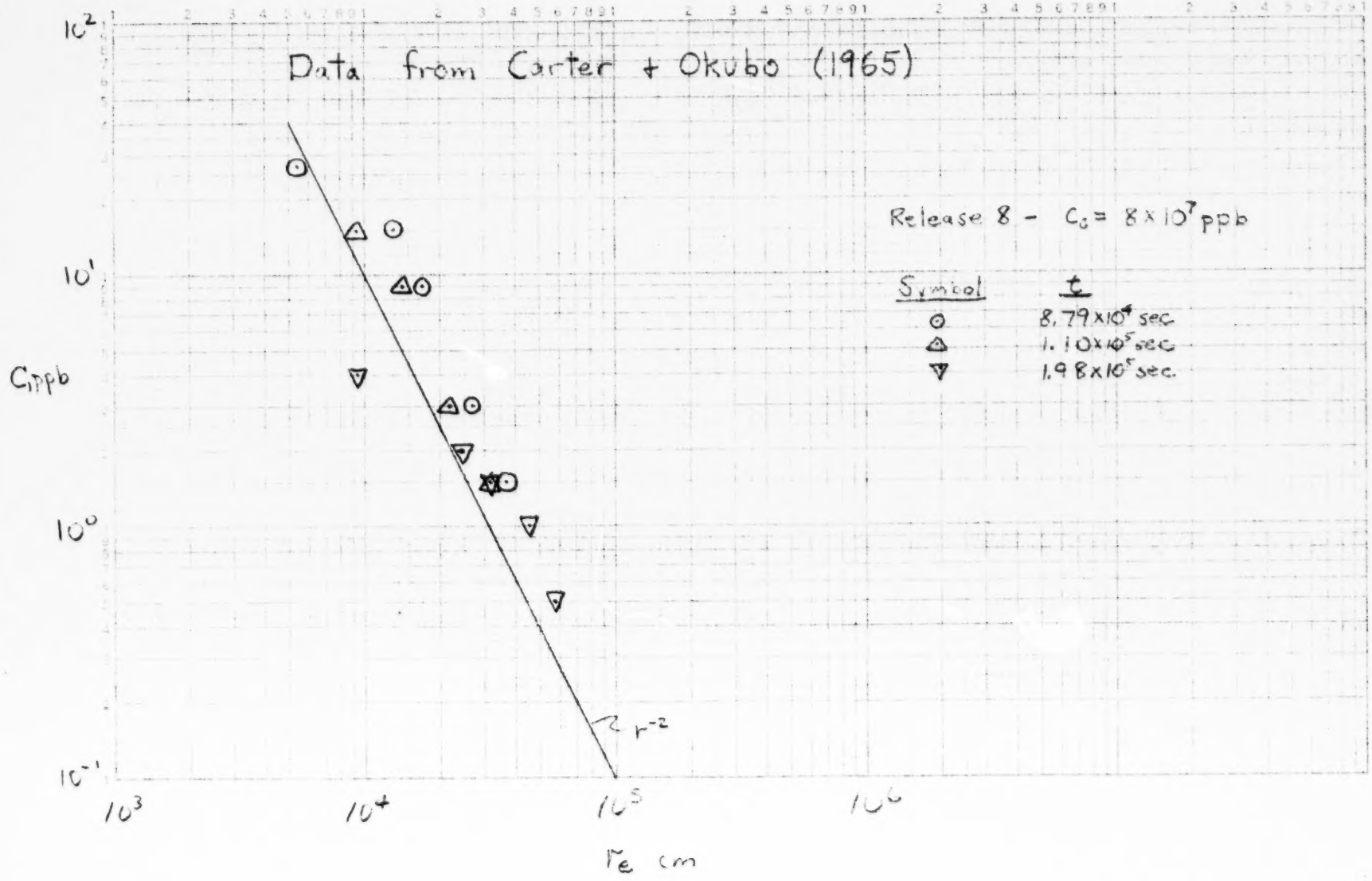

Data from Carter + Okubo (1965)
Release 8 - $C_0 = 8 \times 10^7$ ppb
Symbol t
⊙ 8.79×10^4 sec.
△ 1.10×10^5 sec.
▽ 1.98×10^5 sec.
r^{-2}
C ppb
10^2
10^1
10^0
10^{-1}
10^3
10^4
10^5
10^6
r cm

Fig. 33

Fig. 34

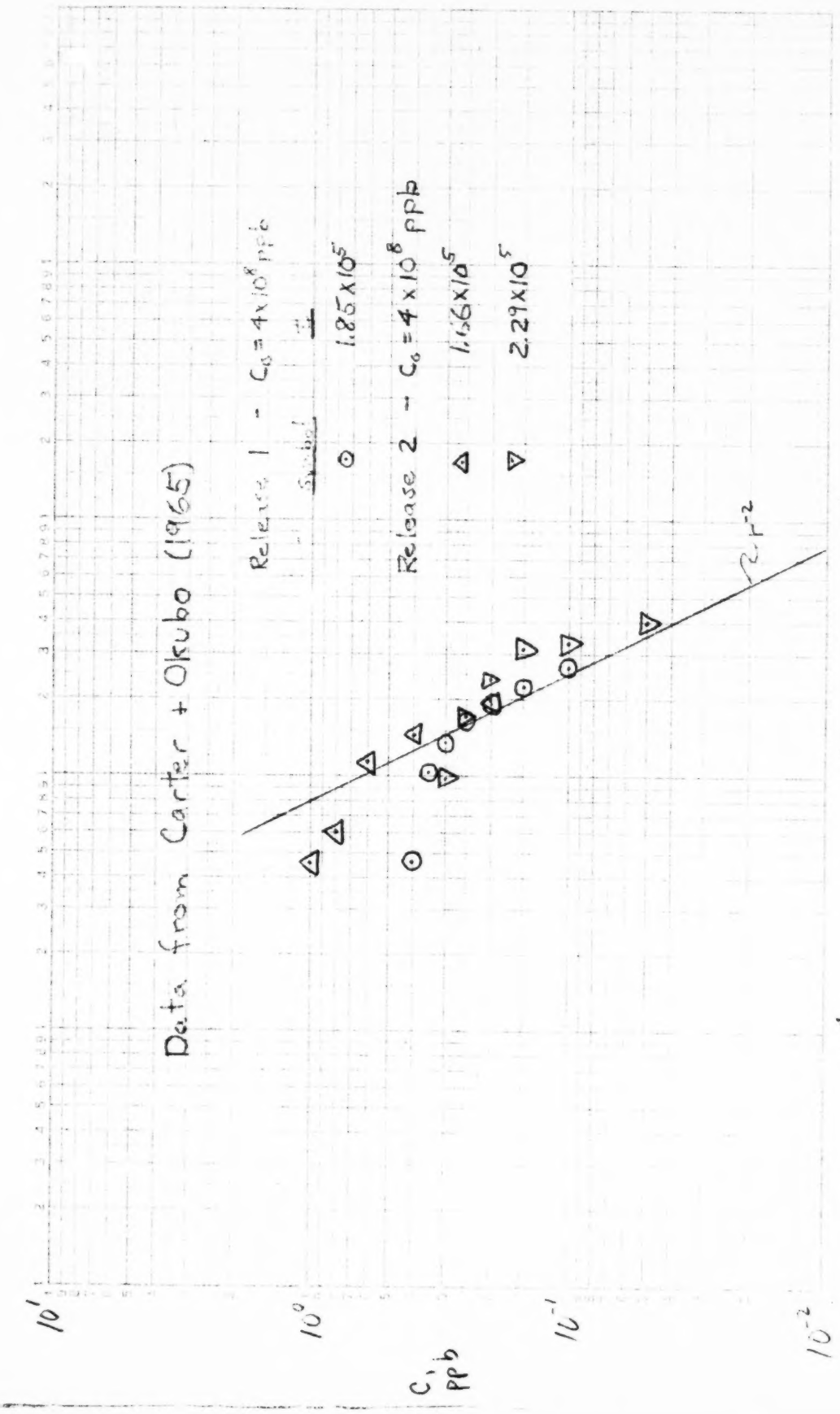
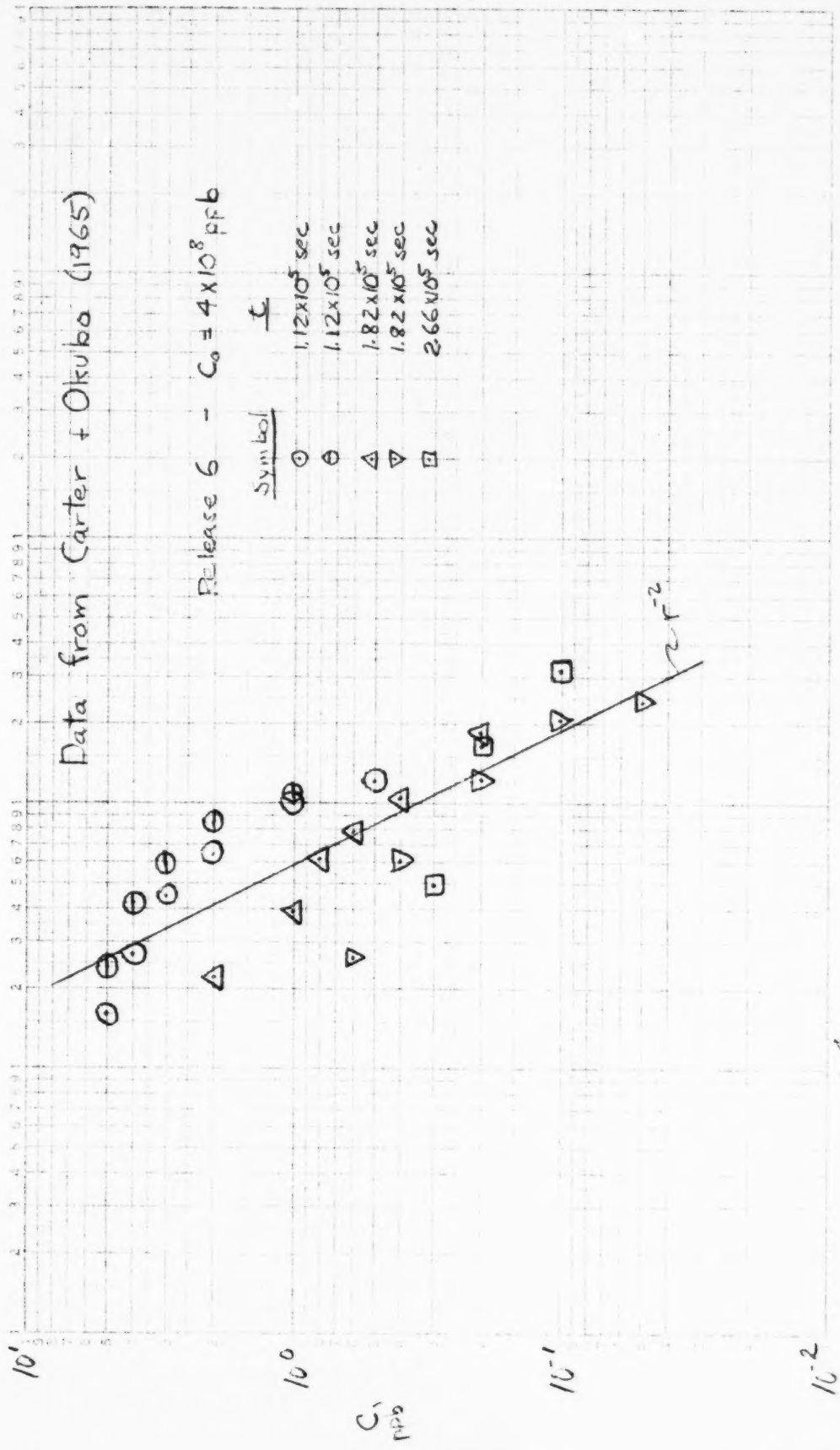

Data from Carter + Okubo (1965)
Release 1 - $C_0 = 4 \times 10^8$ ppb
Symbol
1.85×10^5
Release 2 - $C_0 = 4 \times 10^8$ ppb
1.56×10^5
2.29×10^5
$R \propto r^{-2}$
C, ppb
10^1
10^0
10^{-1}
10^{-2}
10^4
10^5
10^6
Re, cm

Fig. 35


Data from Carter + Okubo (1965)
Release 6 - $C_o = 4 \times 10^8$ pfb
Symbol τ
1.12x10⁵ sec
1.12x10⁵ sec
1.82x10⁵ sec
1.82x10⁵ sec
2.66x10⁵ sec
r^{-2}
10^1
10^0
10^{-1}
10^{-2}
10^4
10^5
10^6
Fe, cm
C, pfb

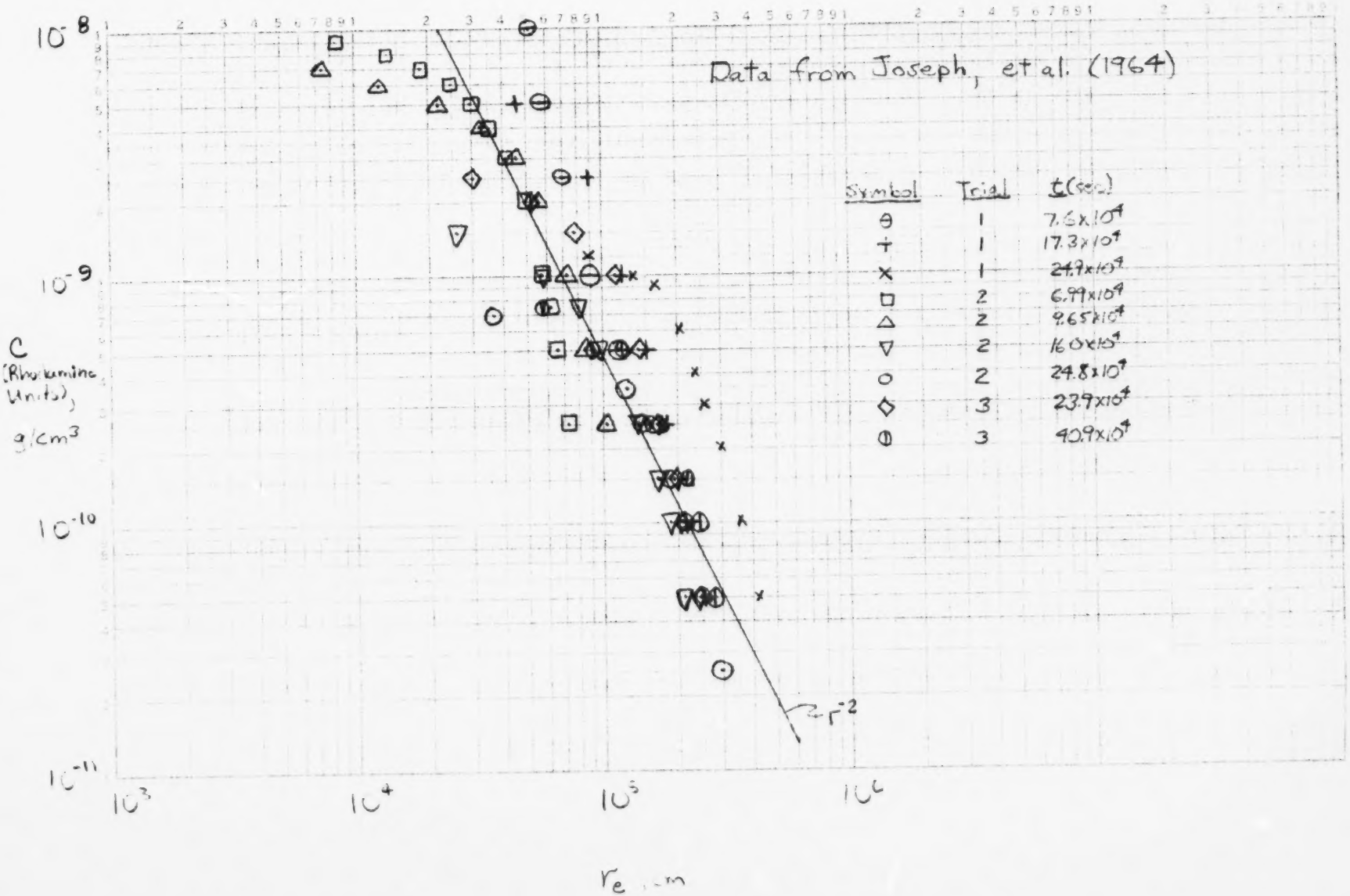

Data from Joseph, et al. (1964)
Symbol | Trial | t(sec)
θ | 1 | 7.6x10^4
+ | 1 | 17.3x10^4
× | 1 | 24.9x10^4
□ | 2 | 6.99x10^4
△ | 2 | 9.65x10^4
▽ | 2 | 16.0x10^4
○ | 2 | 24.8x10^4
◇ | 3 | 23.9x10^4
◐ | 3 | 40.9x10^4
C (Rhodamine Units), g/cm^3
10^-8
10^-9
10^-10
10^-11
10^3
10^4
10^5
10^6
r_e, cm
~r^-2

Fig. 36

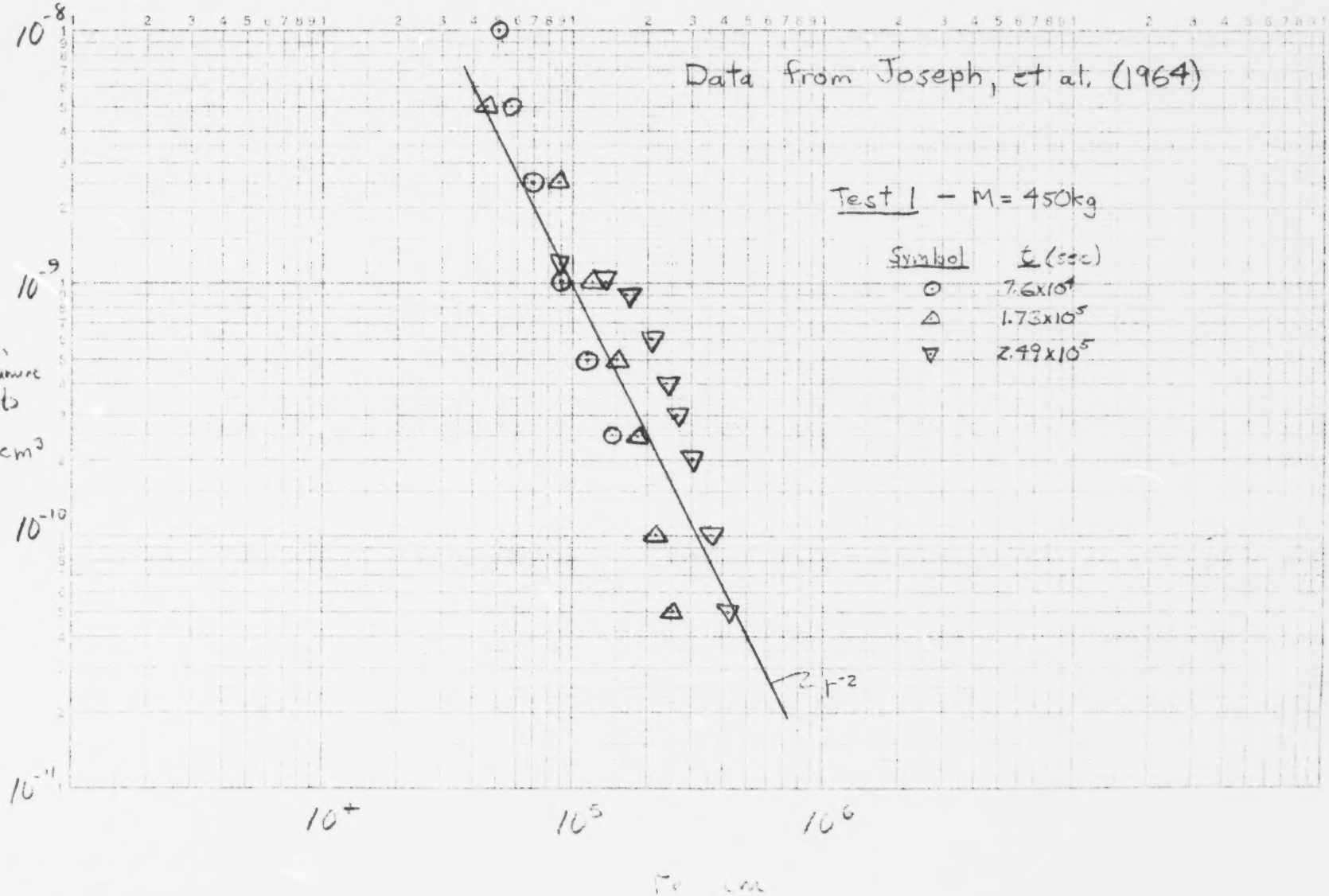

Data from Joseph, et al. (1964)
Test 1 – M = 450kg
Symbol
t (sec)
7.6x10^4
1.73x10^5
2.49x10^5
C, Rhotenuse Units g/cm^3
r^-2
10^-8
10^-9
10^-10
10^-11
10^4
10^5
10^6

Fig. 37

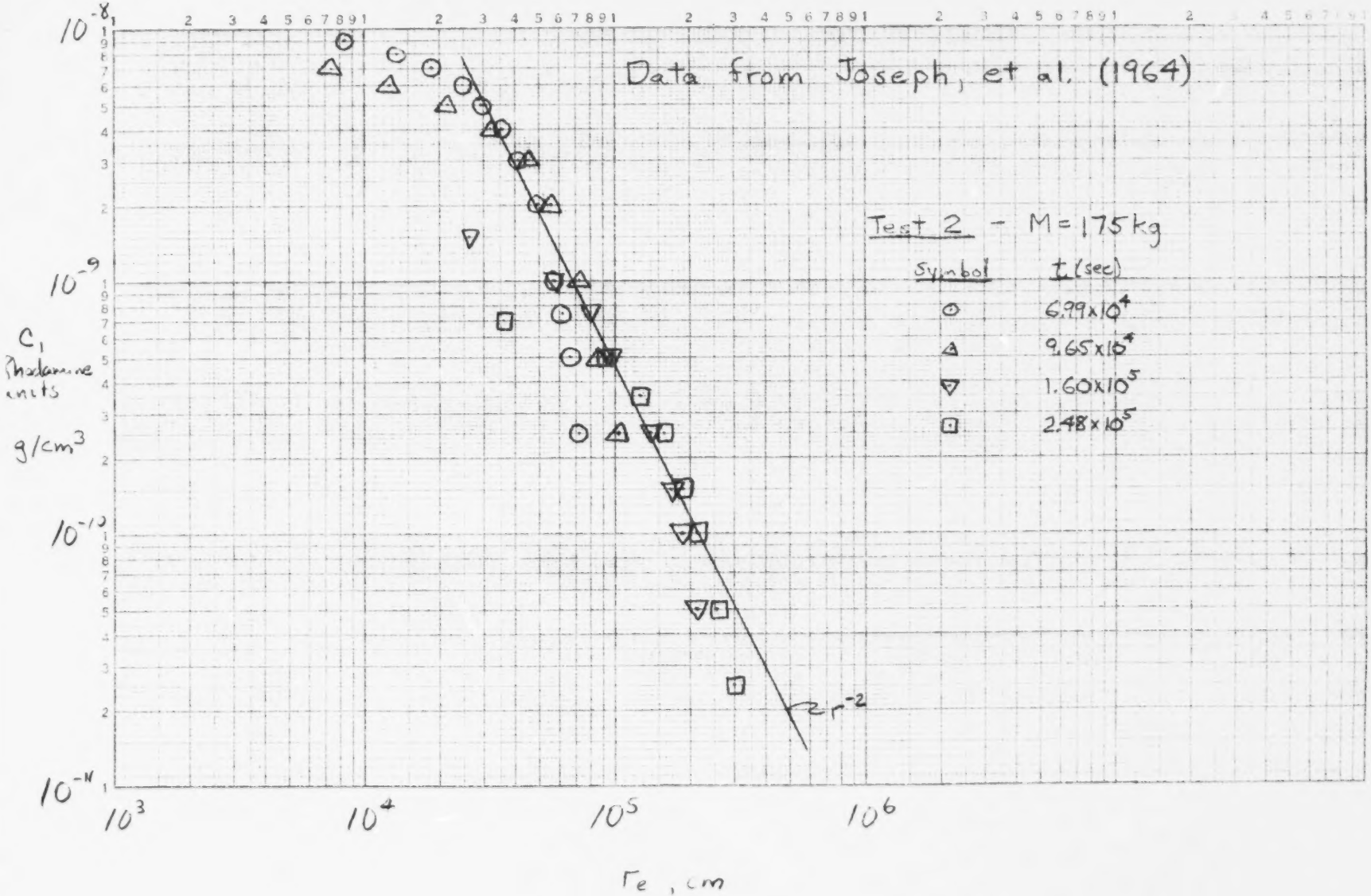

Data from Joseph, et al. (1964)
Test 2 - M = 175 kg
Symbol
t (sec)
6.99x10^4
9.65x10^4
1.60x10^5
2.48x10^5
r^-2
C1 Rhodamine units g/cm^3
Re, cm

Fig. 38

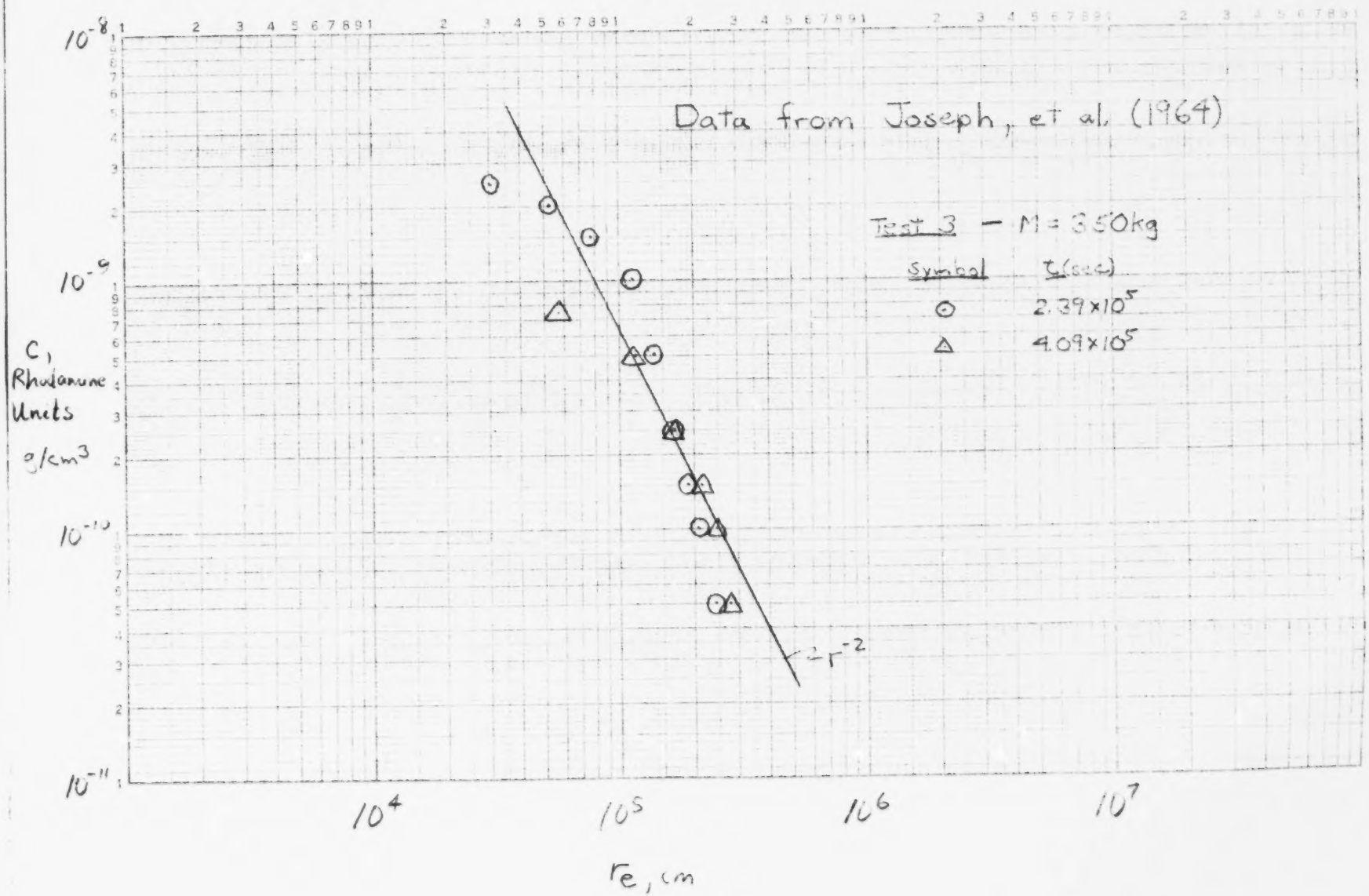

Data from Joseph, et al. (1964)
Test 3 – M = 3.50 kg
Symbol
τ (sec)
⊙ 2.39×10^5
△ 4.09×10^5
r^{-2}
C, Rhotanuine Units g/cm³
r_e, cm
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^4
10^5
10^6
10^7

Fig. 39

Fig. 40

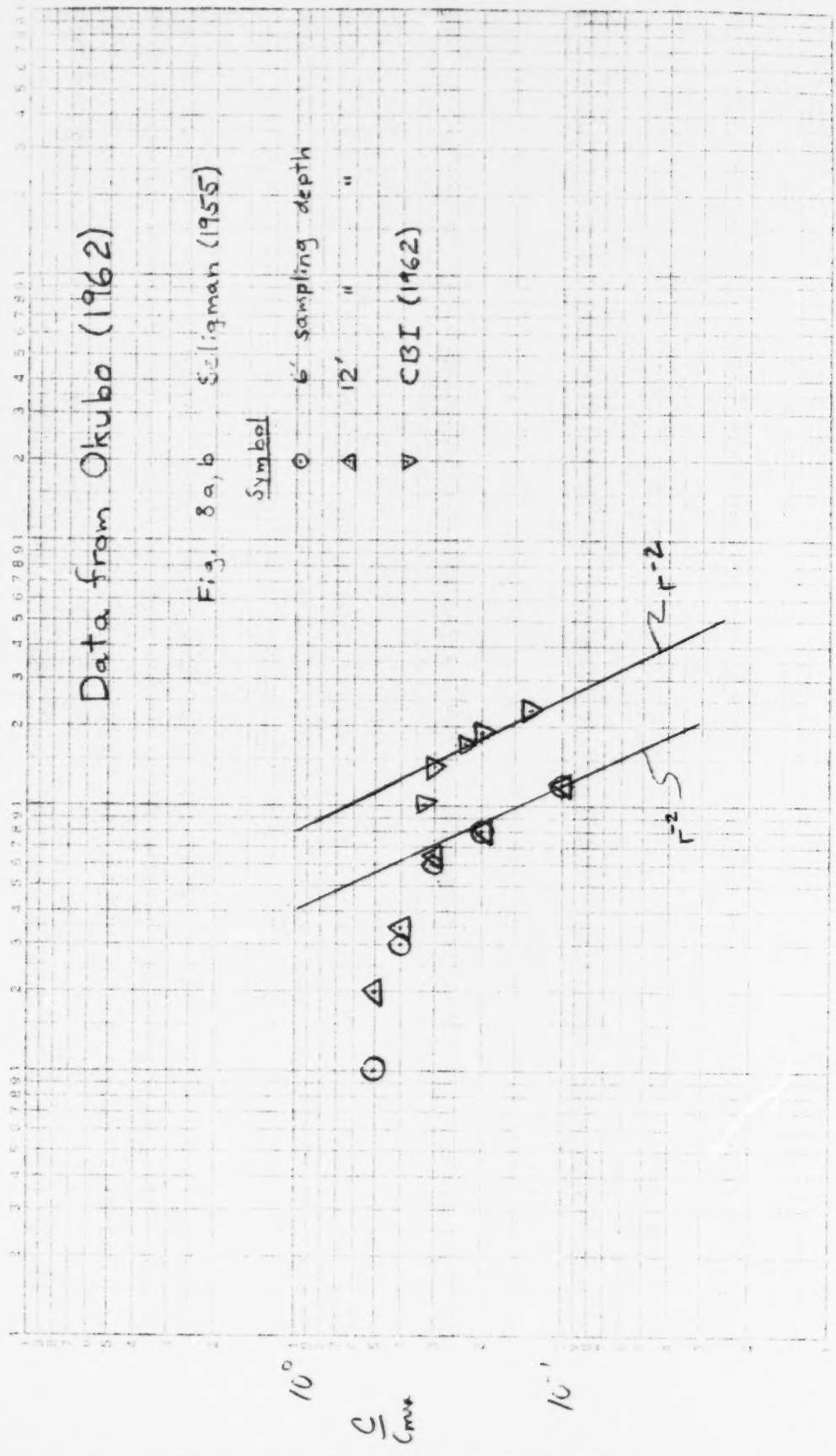
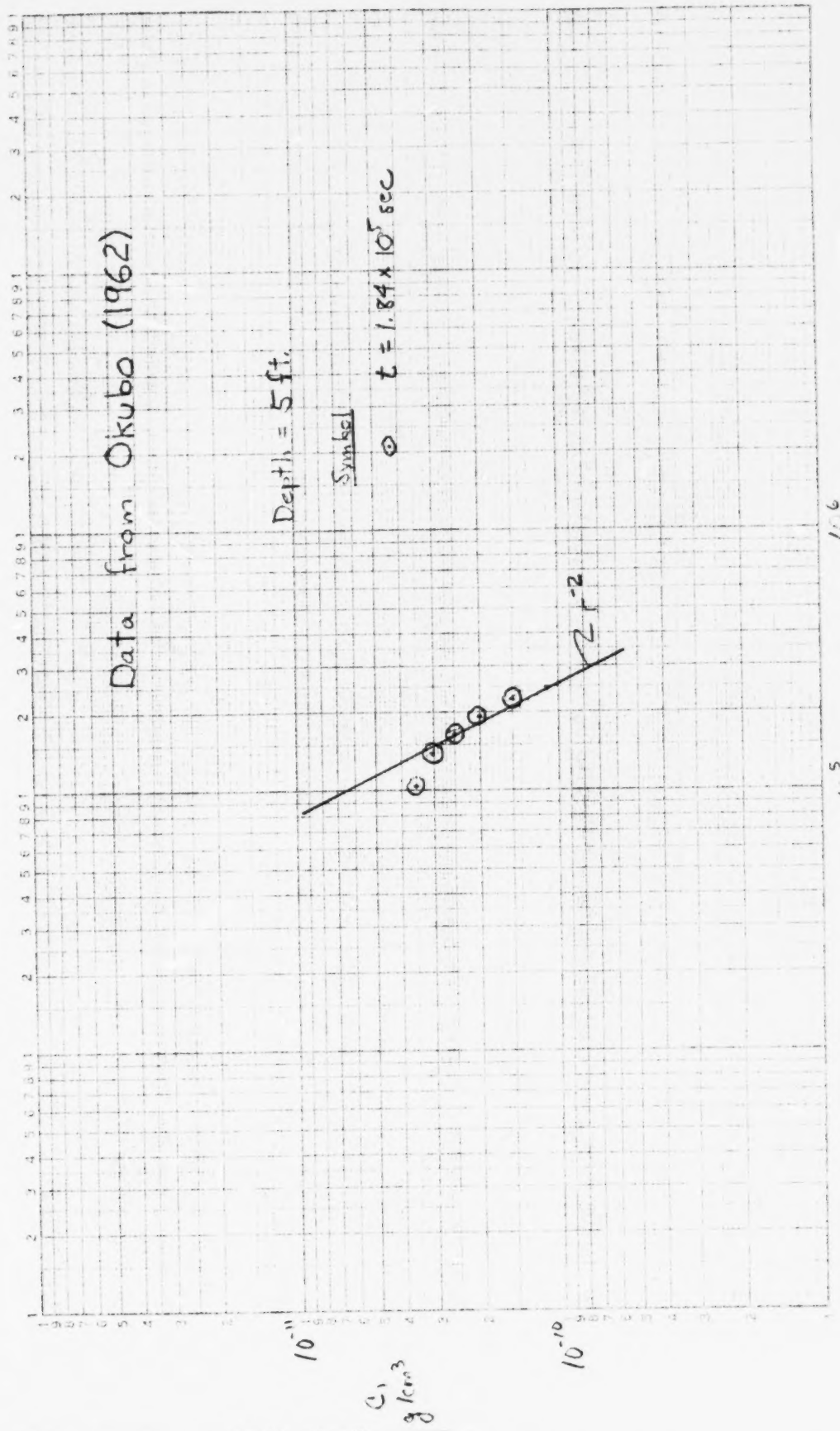

Data from Okubo (1962)
Fig. 8a, b Seligman (1955)
Symbol
6' sampling depth
12' "
CBI (1962)
r^{-2}
r^{-2}
10^0
10^1
10^4
10^5
10^6
Te, cm
$\frac{C}{cm^3}$

Fig. 41


Data from Okubo (1962)
Depth = 5 ft.
Symbol
t = 1.84 × 10^5 sec
2 r^-2
10^-11
10^-10
C, g/cm^3
10^5
10^6
Te, cm

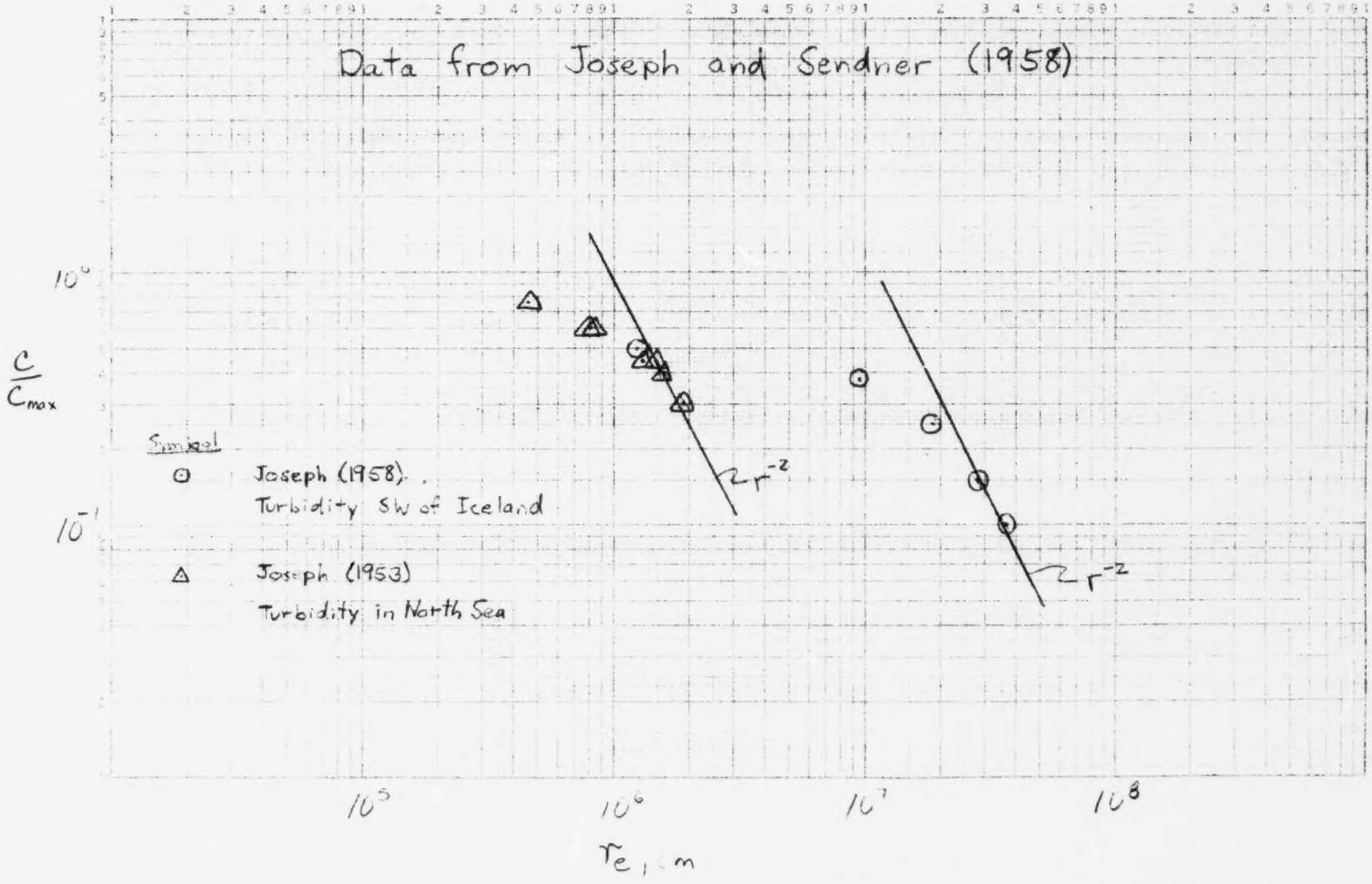

Data from Joseph and Sendner (1958)
$\frac{C}{C_{max}}$
10^0
10^{-1}
Symbol
Joseph (1958)
Turbidity SW of Iceland
Joseph (1953)
Turbidity in North Sea
$\sim r^{-2}$
$\sim r^{-2}$
10^5
10^6
10^7
10^8
$r_{e,cm}$

Fig. 42

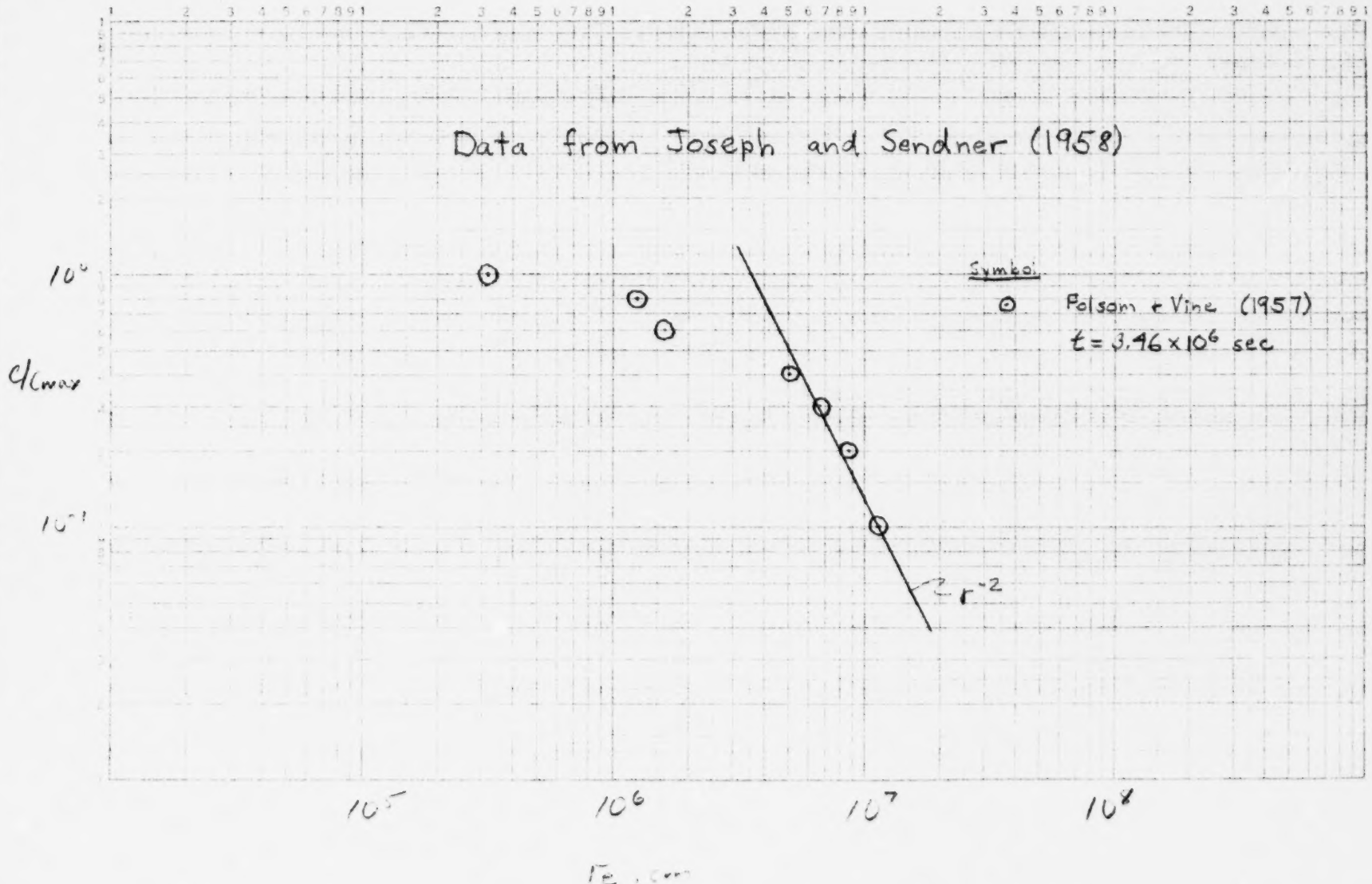

Data from Joseph and Sendner (1958)
Symbol
Folsom + Vine (1957)
t = 3.96 × 10^6 sec
~ r^-2
C/C(max)
10^0
10^-1
10^5
10^6
10^7
10^8
E, ev

Fig. 43

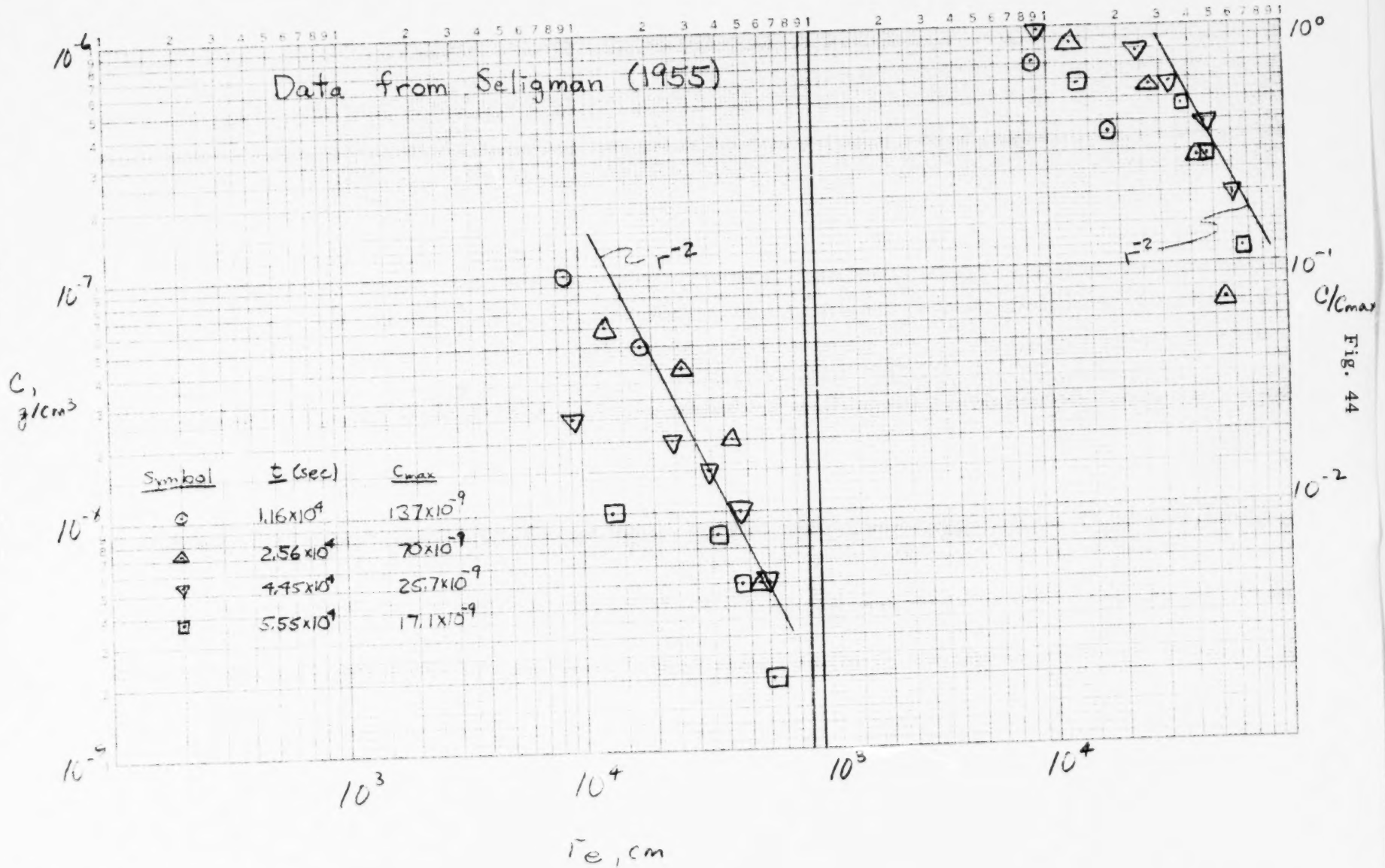

Data from Seligman (1955)
r^{-2}
r^{-2}
C, g/cm³
C/Cmax
r_e, cm
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{0}
10^{-1}
10^{-2}
10^{3}
10^{4}
10^{5}
10^{6}
Symbol | τ (sec) | Cmax
1.16×10⁴ | 137×10⁻⁹
2.56×10⁴ | 70×10⁻⁹
4.45×10⁴ | 25.7×10⁻⁹
5.55×10⁴ | 17.1×10⁻⁹

Fig. 44

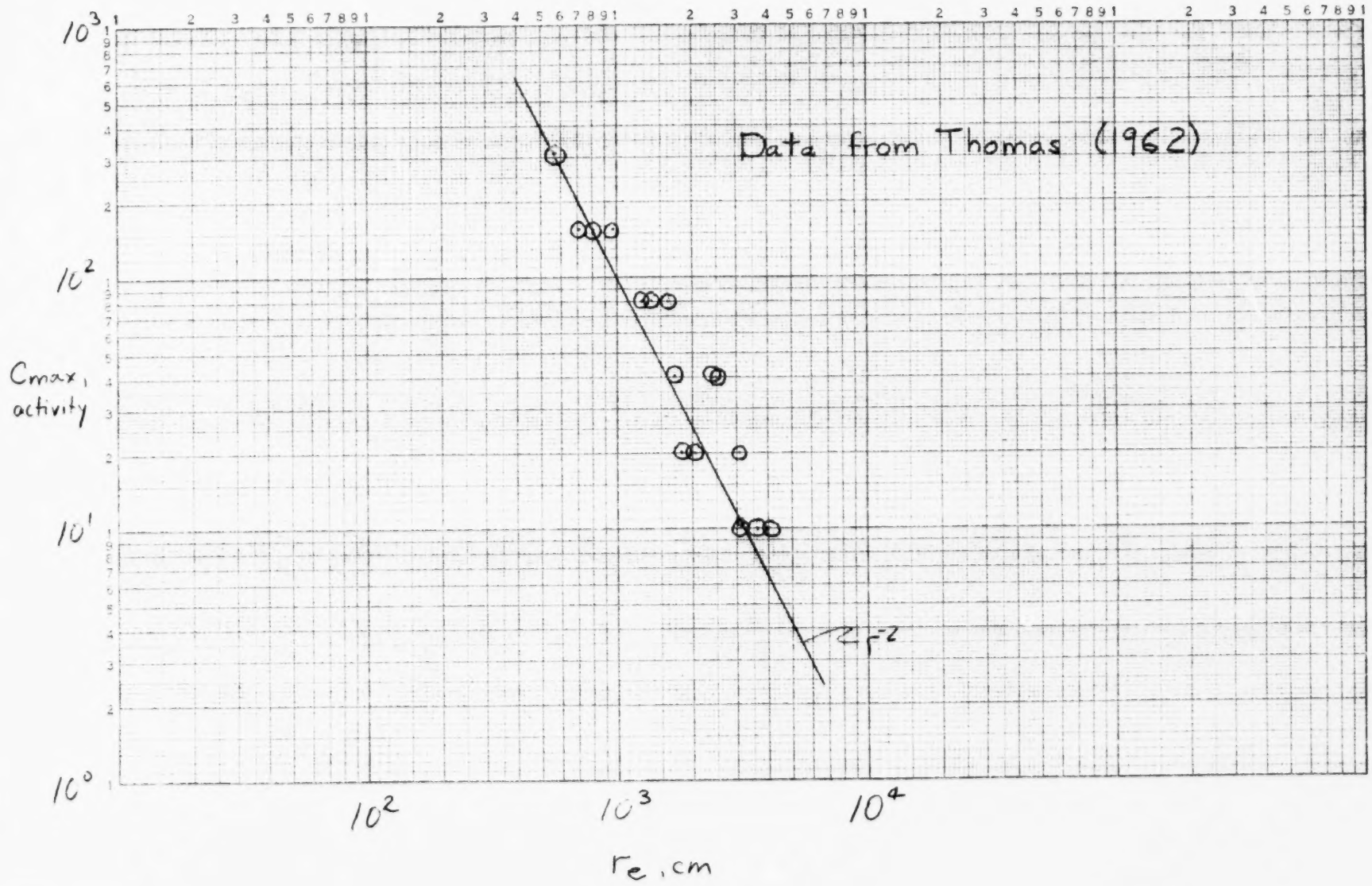

Data from Thomas (1962)
r^{-2}
Cmax, activity
10^3
10^2
10^1
10^0
10^2
10^3
10^4
r_e, cm

Fig. 45